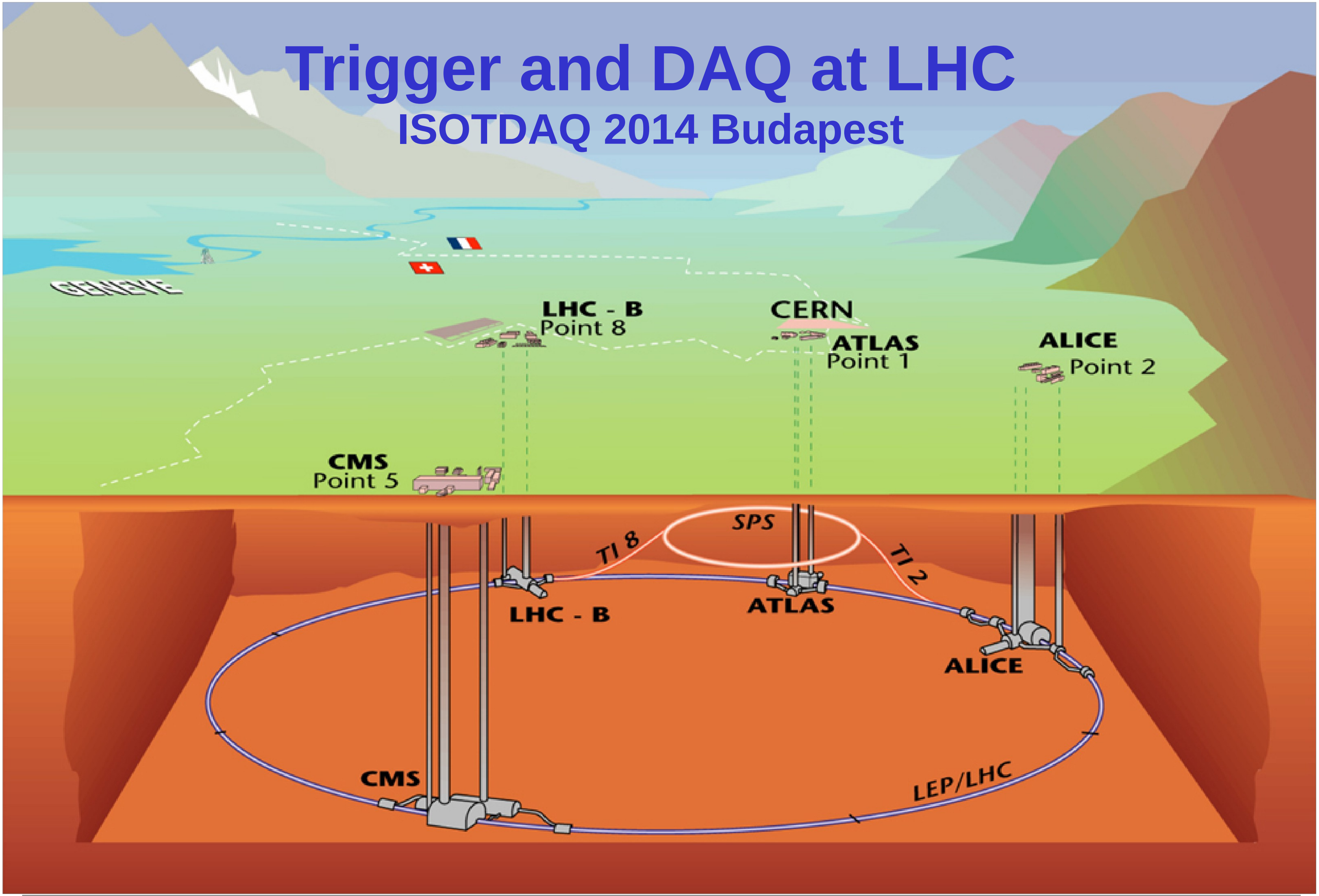
Trigger and DAQ at LHC

ISOTDAQ 2014 Budapest



C.Schwick

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  - Ongoing and future upgrades

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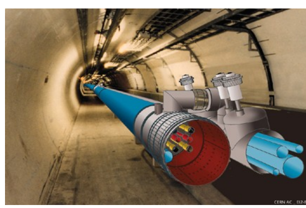
  - Data Flow of the 4 LHC experiments
  - Event Building: CMS as an example
  - Software: Some techniques used in online systems
  - Ongoing and future upgrades

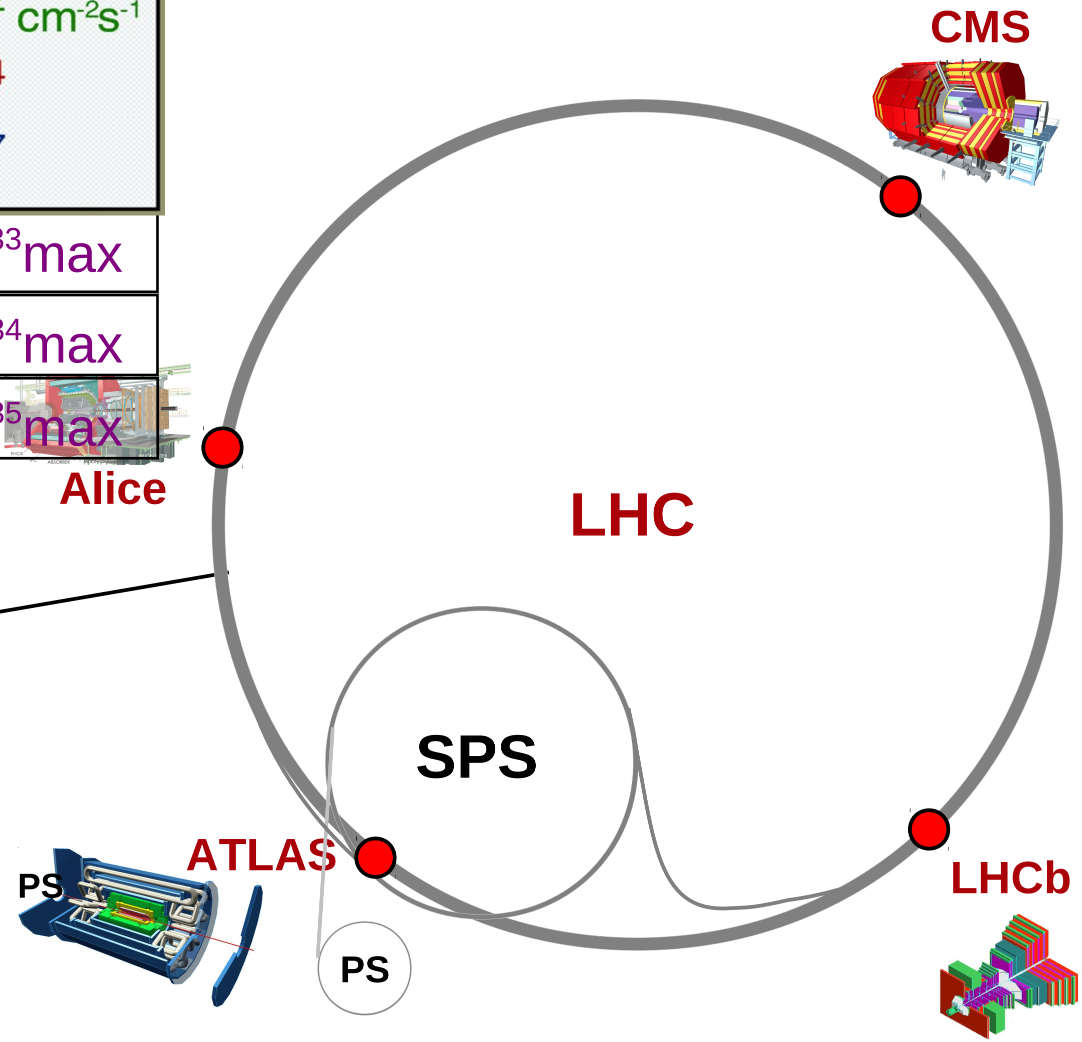
- **Acknowledgement**
  - Thanks to many of my colleagues in ALICE, ATLAS, CMS, LHCB for the help they gave me while preparing these lectures; and in particular to Sergio Cittolin who provided me with many slides (probably those you will like most are from him!)

Introduction: LHC and the Experiments

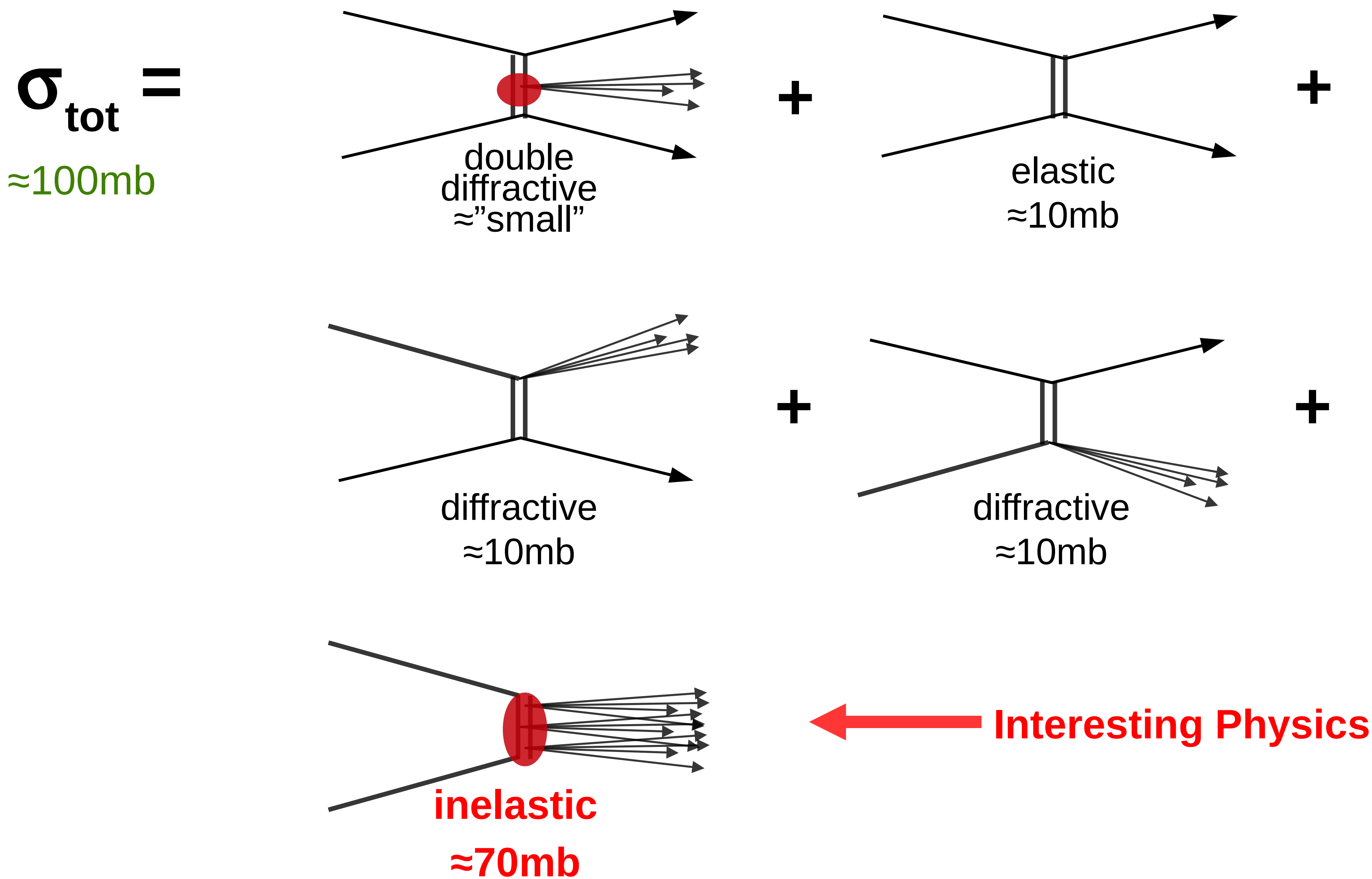
LHC: a "discovery" machine

	Beams	Energy		Luminosity
LEP	e^+e^-	200	GeV	10^{32} $cm^{-2}s^{-1}$
LHC	p p	14	TeV	10^{34}
	P_b P_b	1312	TeV	10^{27}
LHC 2012	pp	8	TeV	$7x10^{33}$max
LHC 2015	pp	13	TeV	$2x10^{34}$max
LHC 2023	pp	13	TeV	$1x10^{35}$max

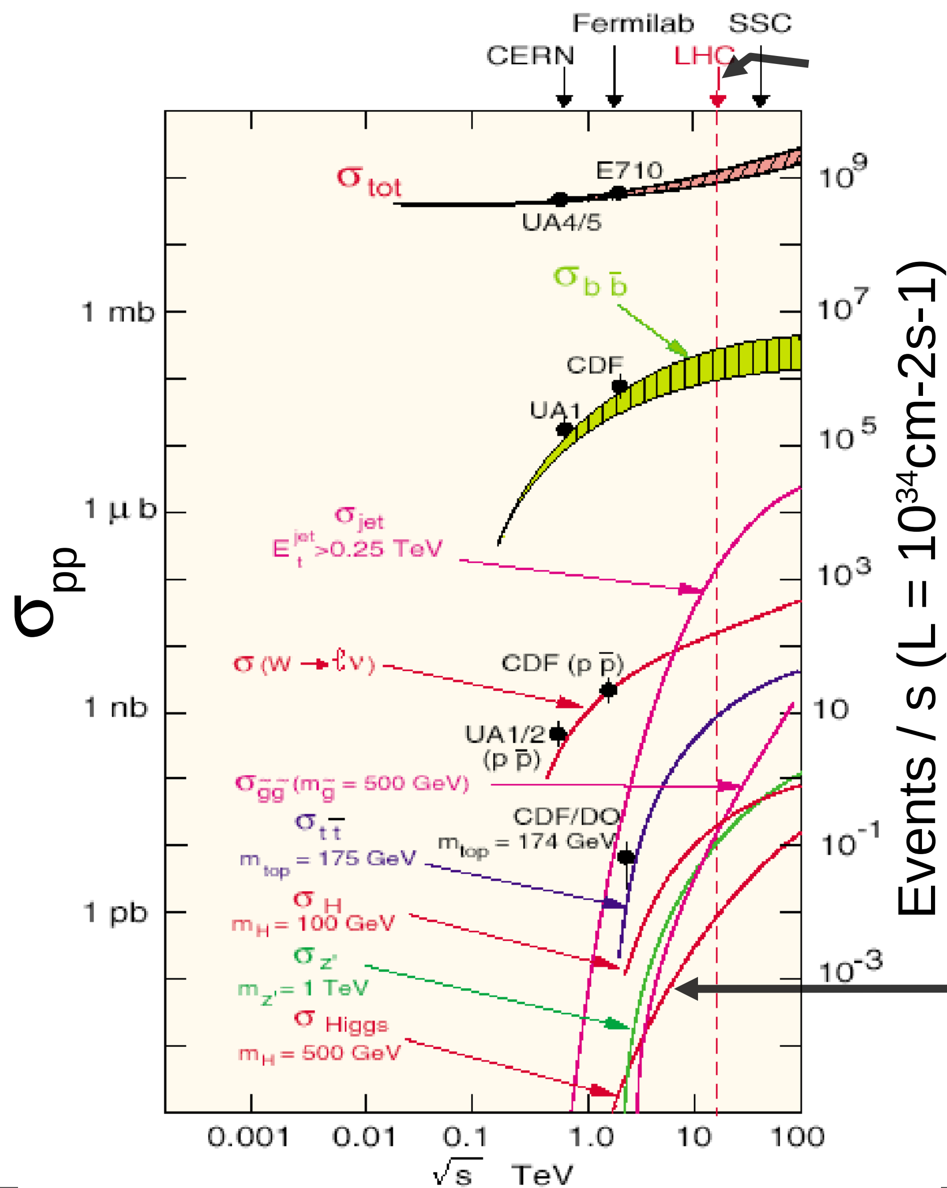




p-p interactions at LHC



Interesting Physics at LHC



$\sigma_{tot} \approx 100$ mb

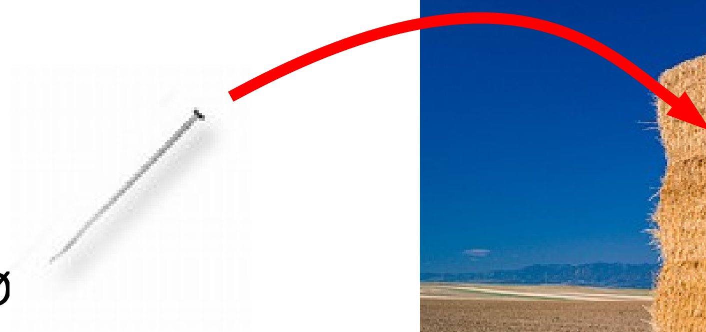
1 : 100 000 000 000

$\sigma_{H(500GeV)} \approx 1$ pb

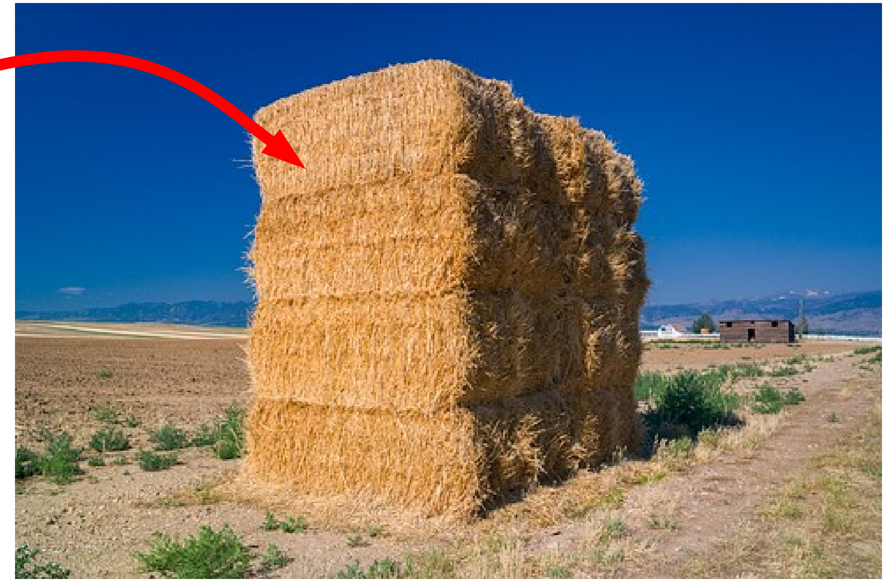
a needle in the haystack

Is the Higgs a needle in the hay stack?

- **Hay stem:**
  - 500mm length, 2mm Ø
    → 3000 mm^3



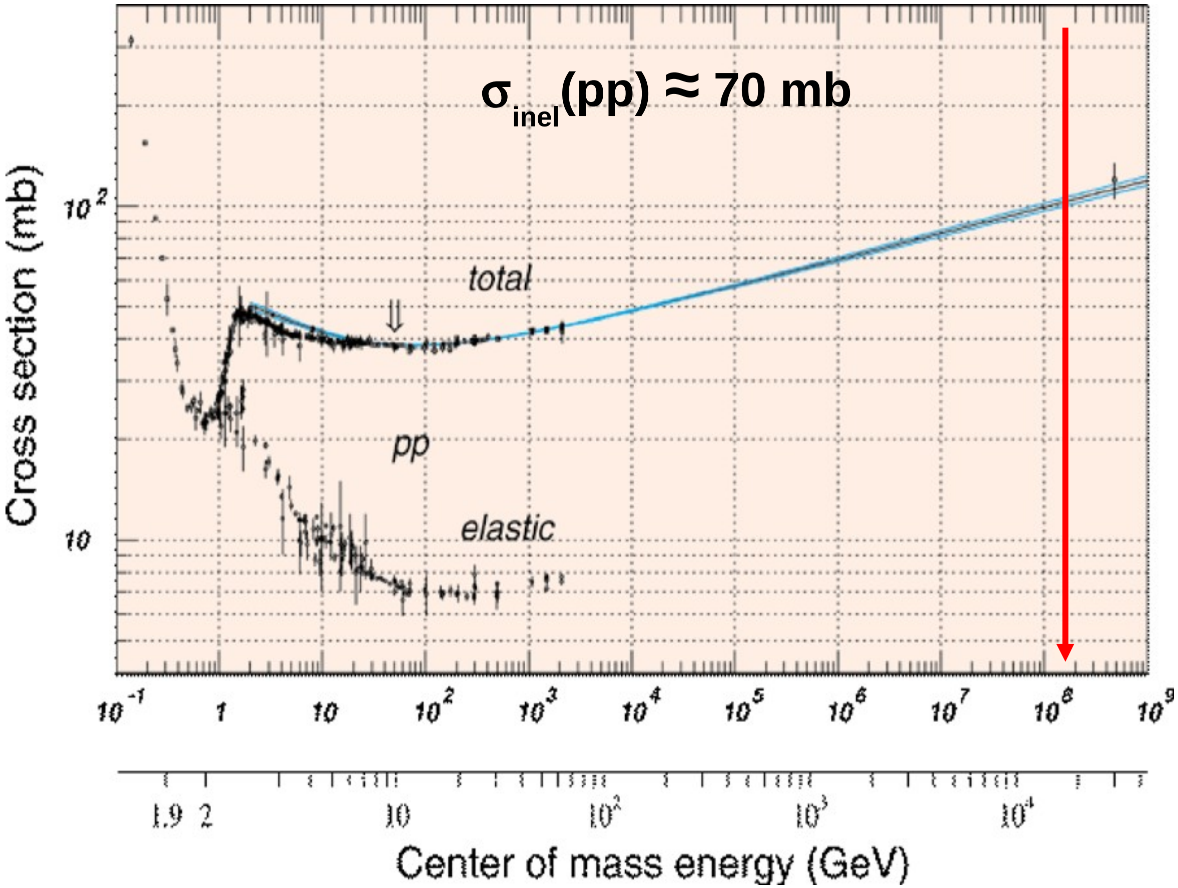
- **Needle**
  - 50 mm length, 0.3mm Ø
    → 50 mm^3
  - 50 needles are one hay stem



- **Putting it all together**
  - Assume hay packing density of 10
    (...may be optimistic...)

    Haystack of 50 m^3

LHC: experimental environment



$L = 10^{34} cm^{-2}s^{-1}$

$\sigma_{inel}(pp) \approx 70$mb

event rate = 7 x 10^8 Hz

Δt = 25ns

events / 25ns = 17.5

Not all bunches full (2835/3564)

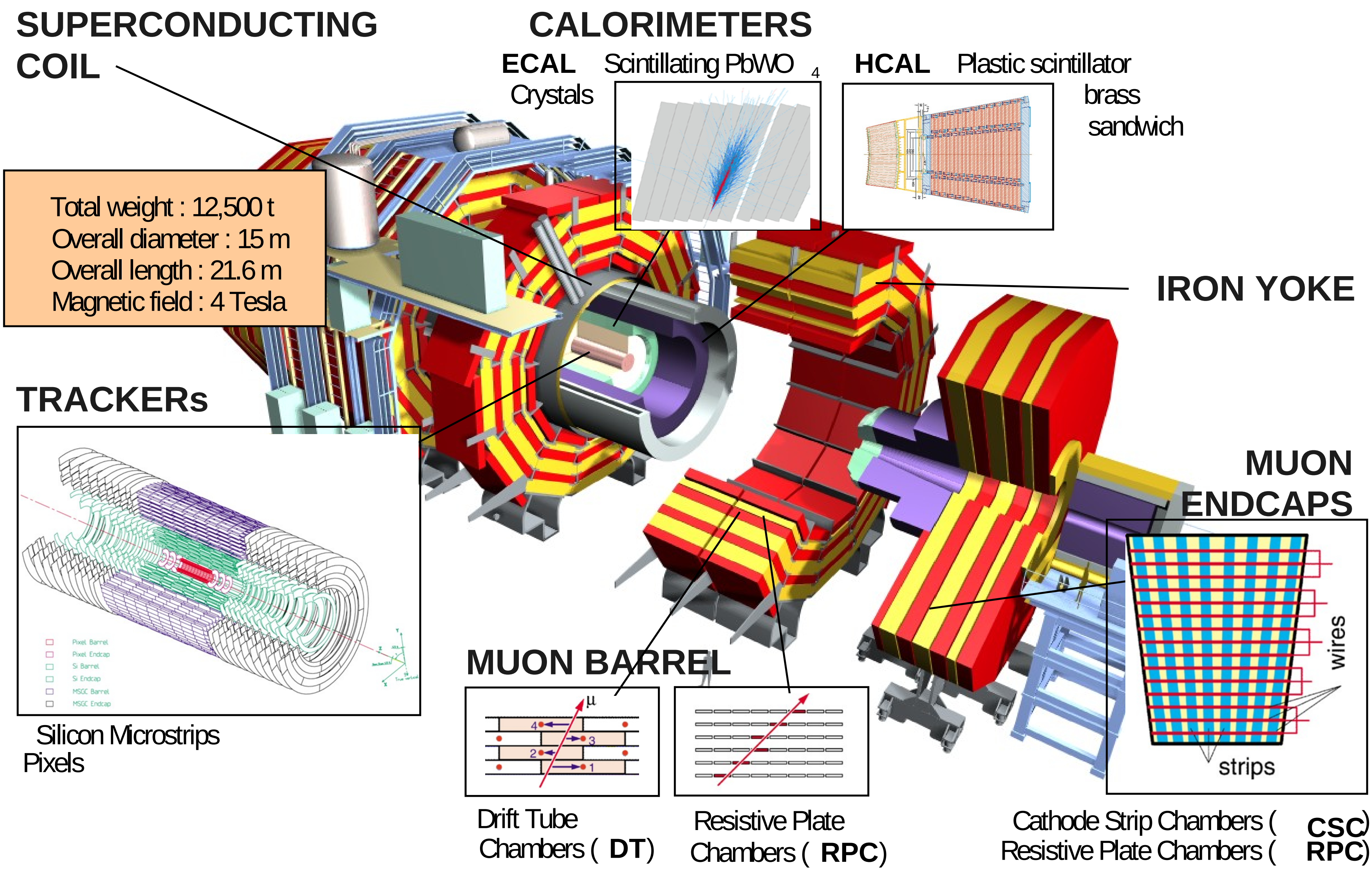
events/crossing = 23

2012 LHC ran at 50ns
pile up was twice as high as for 25 ns (at constant Lumi)

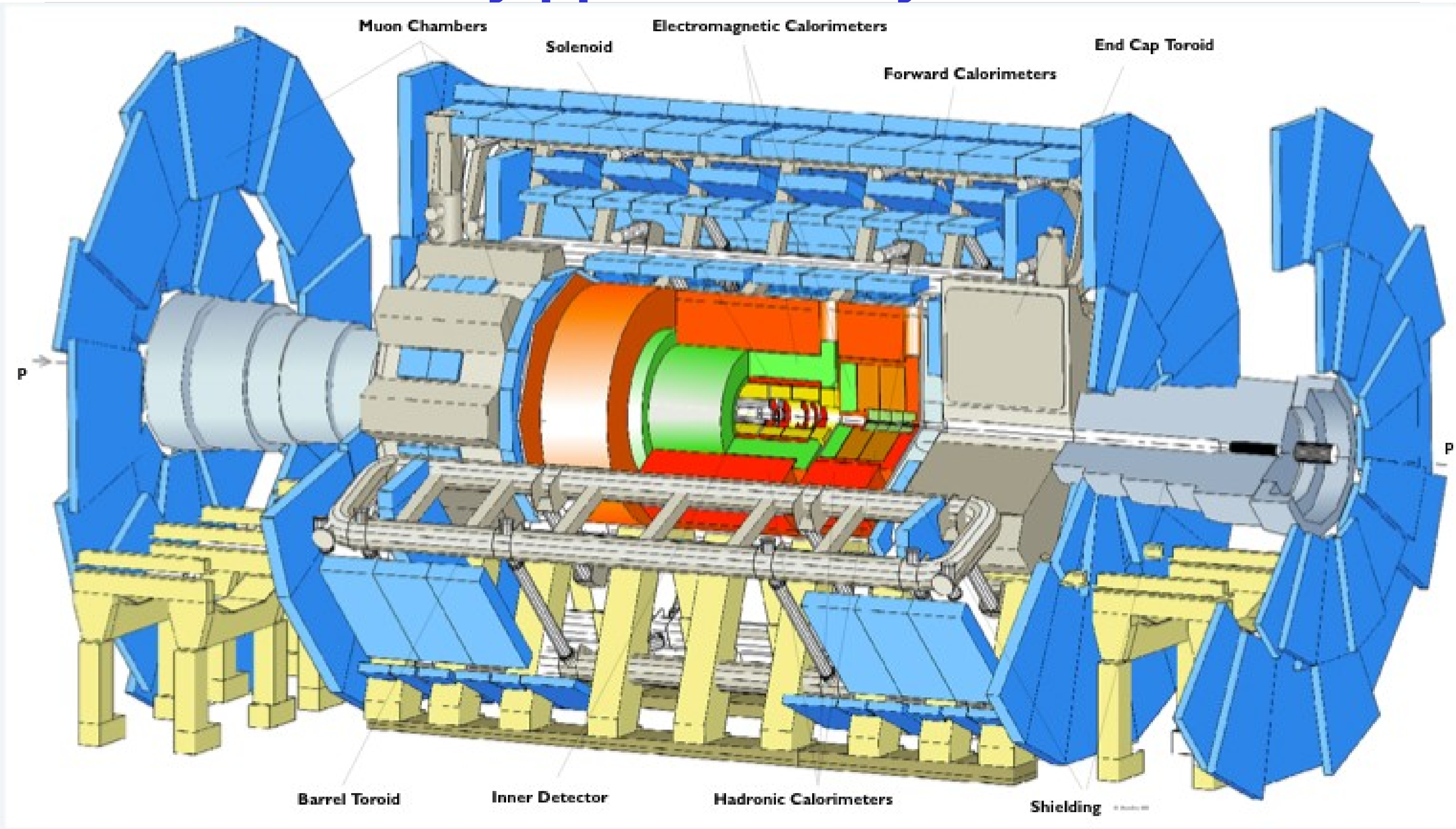
The 4 largest LHC experiments

CMS : study pp and heavy ion collisions

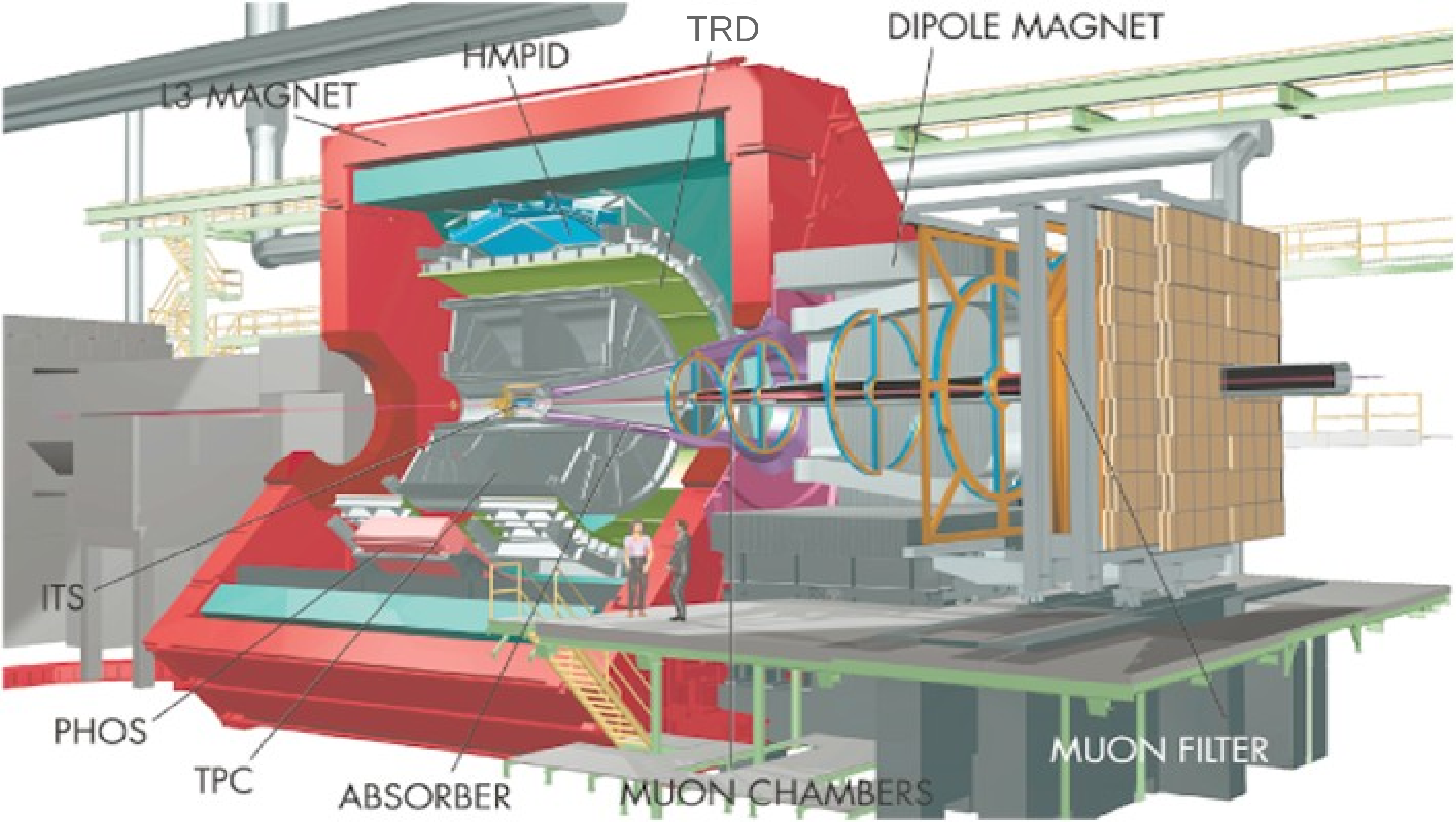
Total weight : 12,500 t
Overall diameter : 15 m
Overall length : 21.6 m
Magnetic field : 4 Tesla



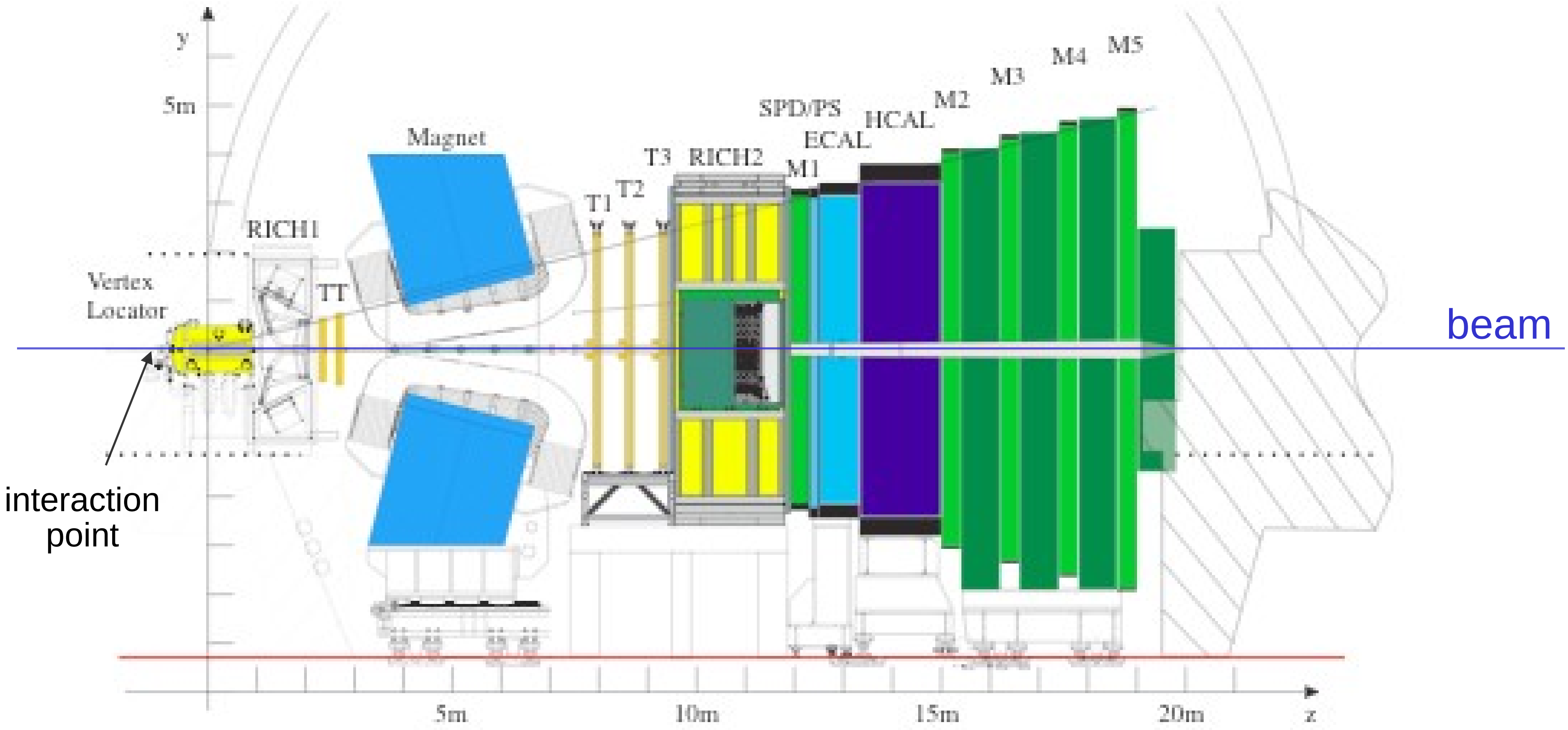
Atlas : study pp and heavy ion collisions



ALICE : study heavy ion collisions

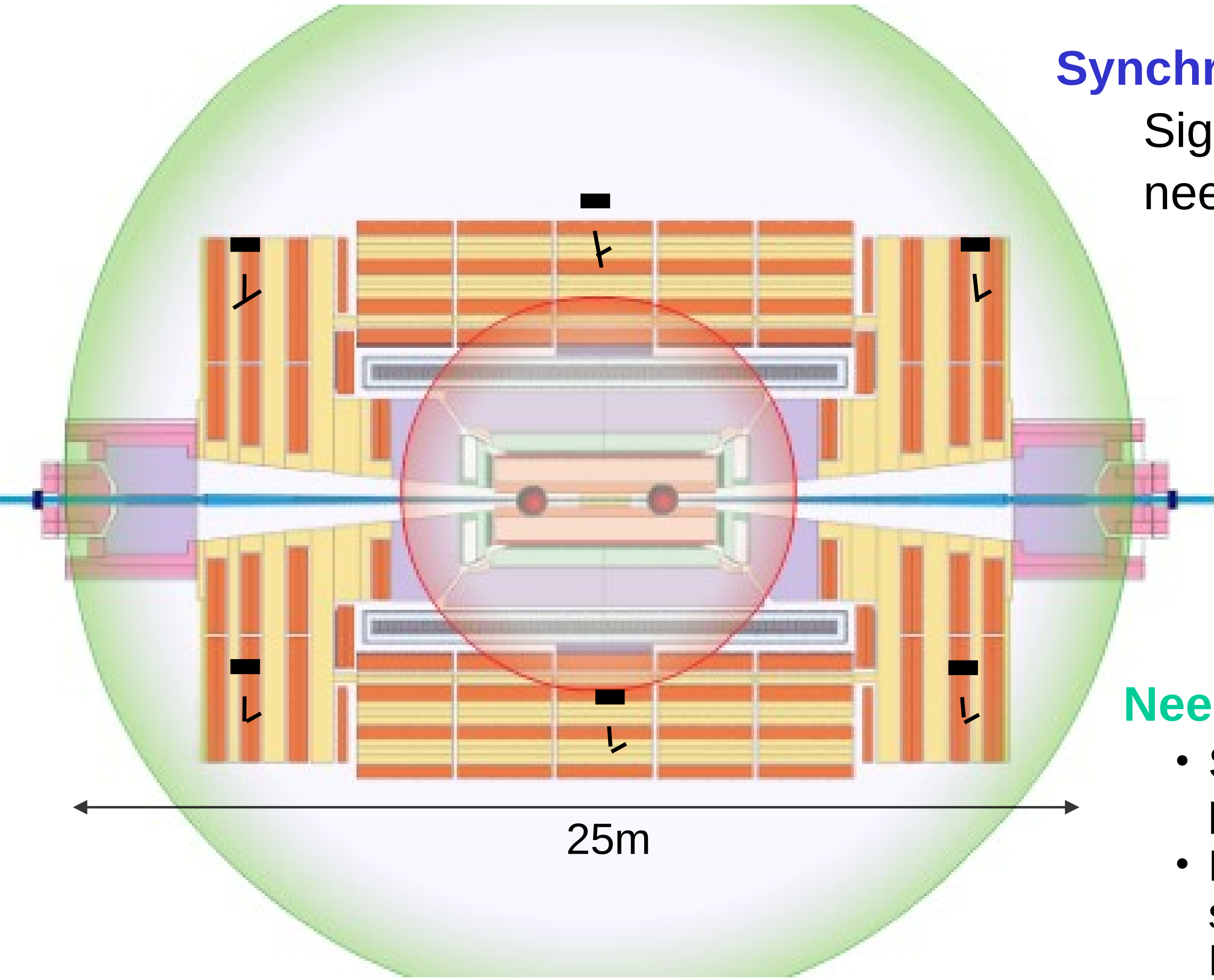


LHCb : study of B-decays ($\not{CP}$)



Timing and Synchronization

Issue: synchronization



Synchronization:

Signals/Data from the same BX need to be processed together

But:

Particle TOF >> 25ns

(25 ns ≈ 7.5m)

Cable delay >> 25ns

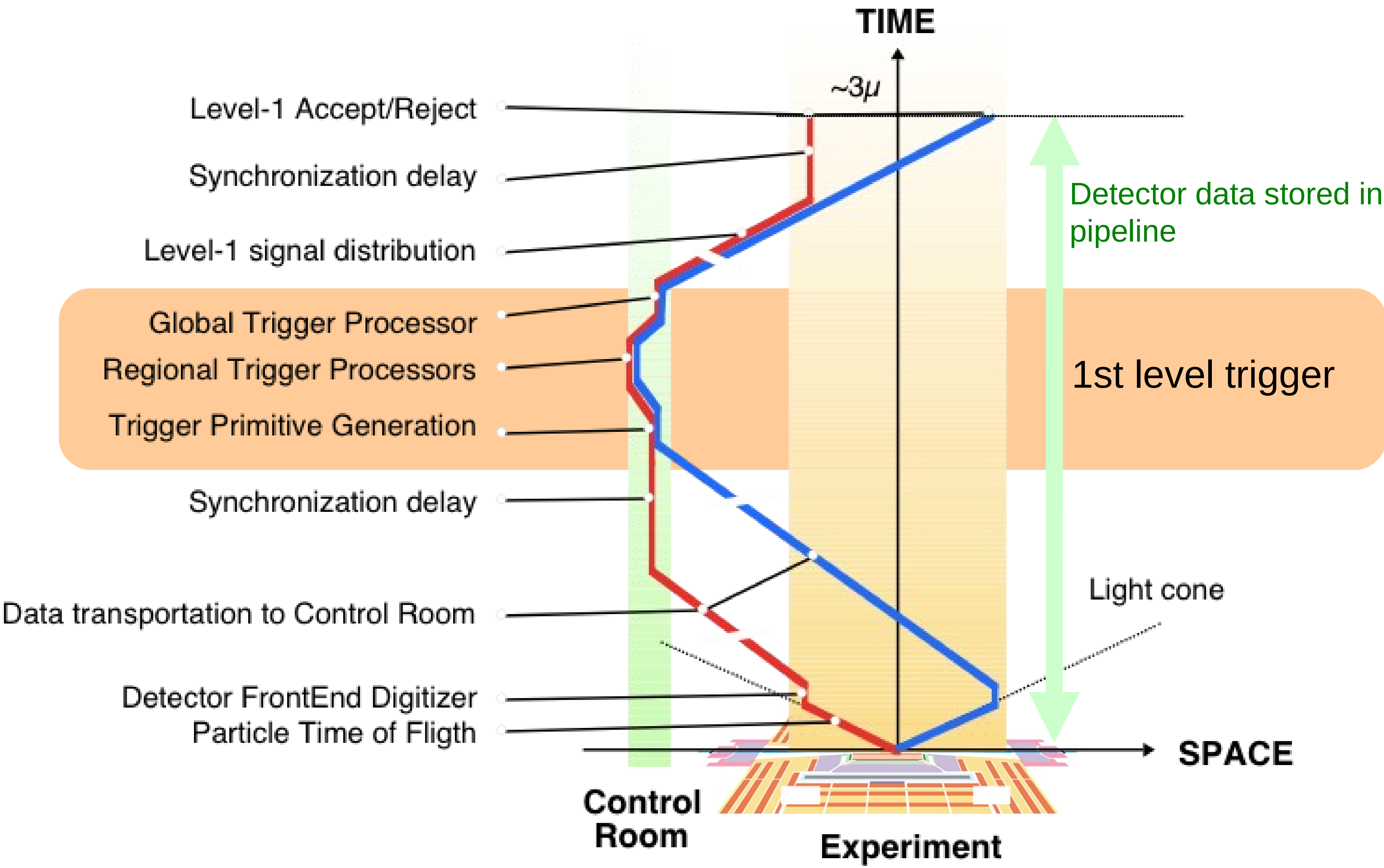
(v_{signal} ≈ 1/3 c)

Electronic delays

Need to:

- Synchronize signals with programmable delays.
- Provide tools to perform synchronization (TDCs, pulsers, LHC beam with few buckets filled…)

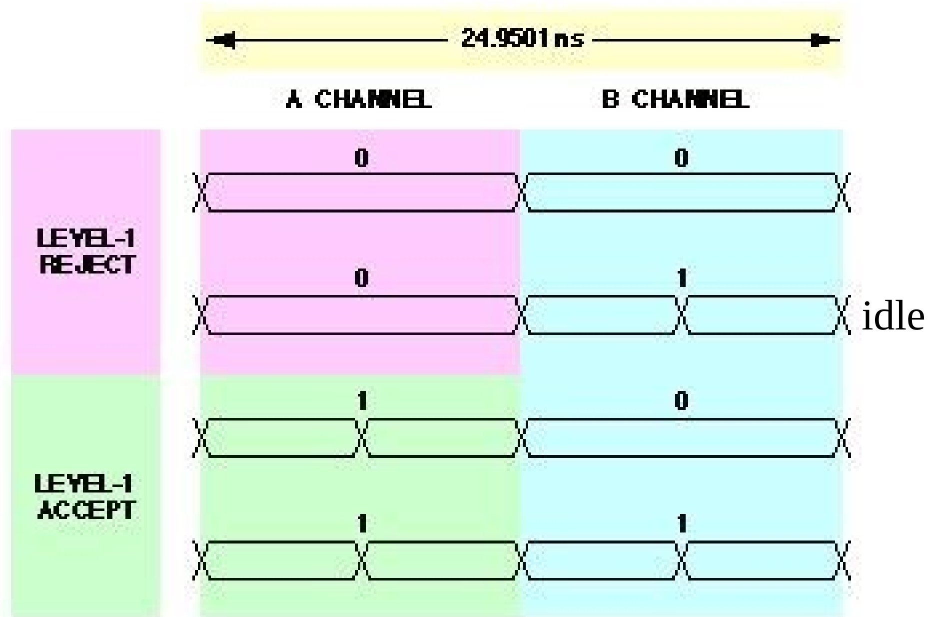
Signal path during trigger



Distribution of Trigger signals

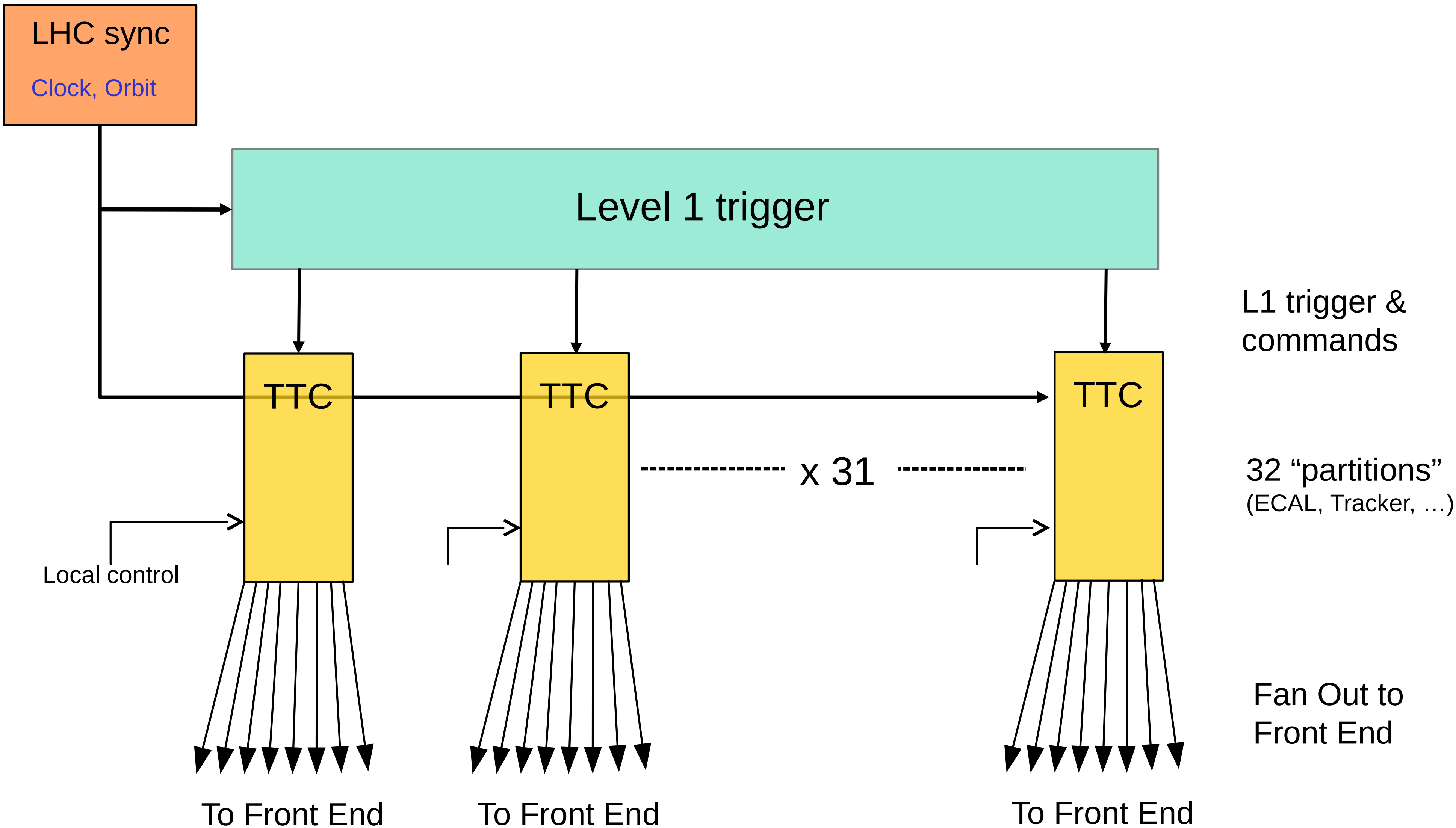
- **The L1 trigger decision needs to be distributed to the front end electronics**
  - Triggers the readout of pipeline
  - Needs to allow to determine the Bunch Crossing of the interaction
    - Timing needs to be precise (low jitter, much below 1ns)
    - Signal needs to be synchronized to LHC clock
- **In addition some commands need to be distributed:**
  - always synchronous to LHC clock; e.g.
    - To do calibration in LHC gap (empty LHC buckets)
    - Broadcast reset and resynchronization commands
- **Used by all experiments: TTC (Trigger Timing and Control)**

TTC encoding: 2 Channels



- **Channel A:**
  - One bit every 25ns
  - constant latency required
    - Used to read out pipelines
  - For distribution of LVl1-accept
- **Channel B:**
  - One Bit every 25 ns
  - Synchronous commands
    - Arrive in fixed relation to LHC Orbit signal
  - Asynchronous commands
    - No guaranteed latency or time relation
  - "Short" broadcast-commands (Bunch Counter Reset, LHC-Orbit)
  - "Long" commands with addressing scheme
    - Serves special sub-system purposes

Trigger, Timing, Control at LHC



First Level Trigger

Three very different real world examples

	LEP	DaΦne	LHC
physics	e+ / e-	e+ / e-	p / p
Event size	O(100 kB)	O(5 kB)	2013: (1MB for CMS & ATLAS)
1/fBX	22µs (later 11µs)	2.7 ns	25 ns
Lvl1 Trig.	Decision between 2 bunch crossings	Continuously running; trigger readout on activity	2013: Synchronous to 40Mhz base clock; decision within 3us latency; pipeline
trigger rate	O(10Hz)	50kHz	2013: 100kHz (1MHz LHCb)
			2023: 1MHz (40MHz LHCb)

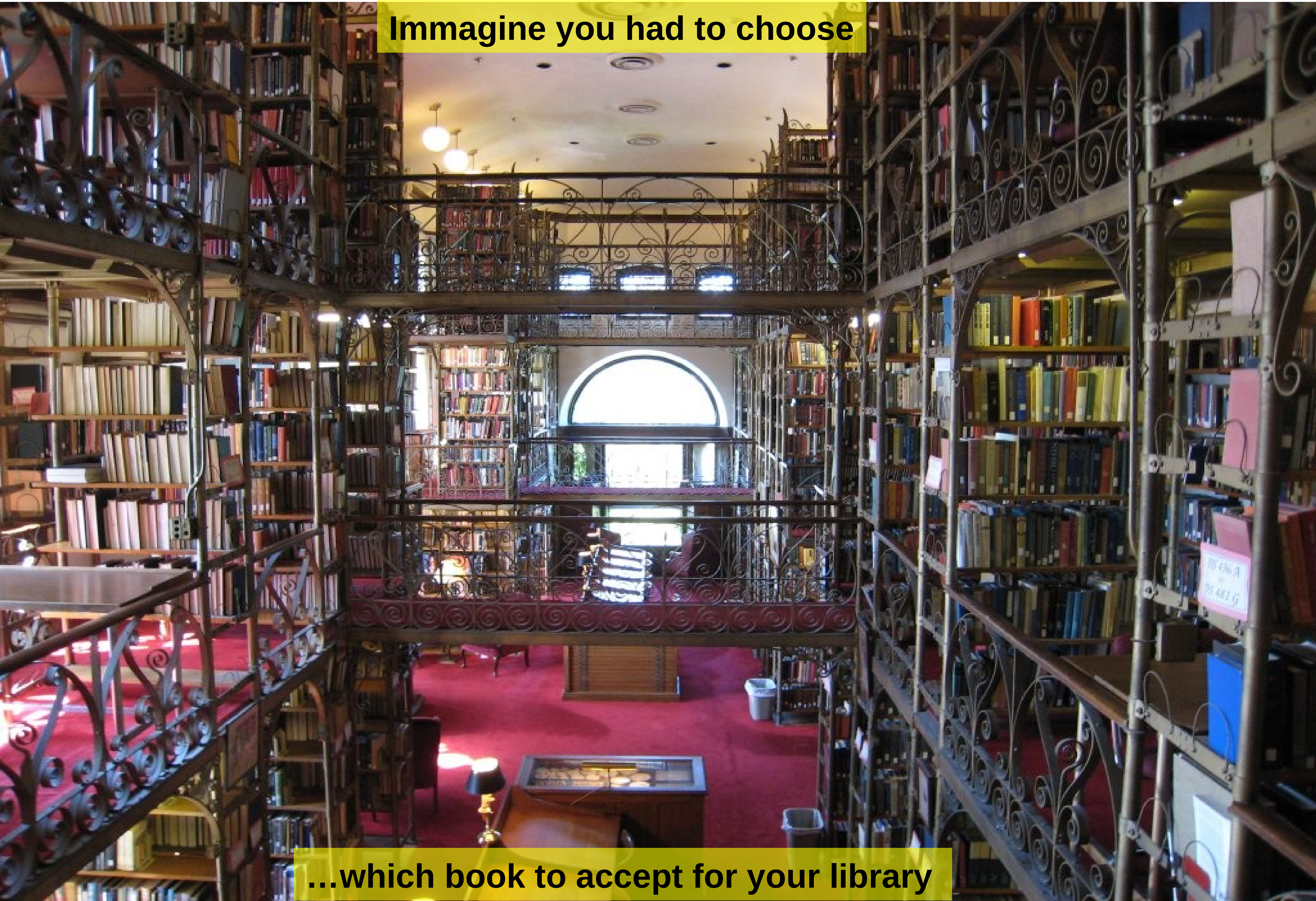


Immagine you had to choose
…which book to accept for your library

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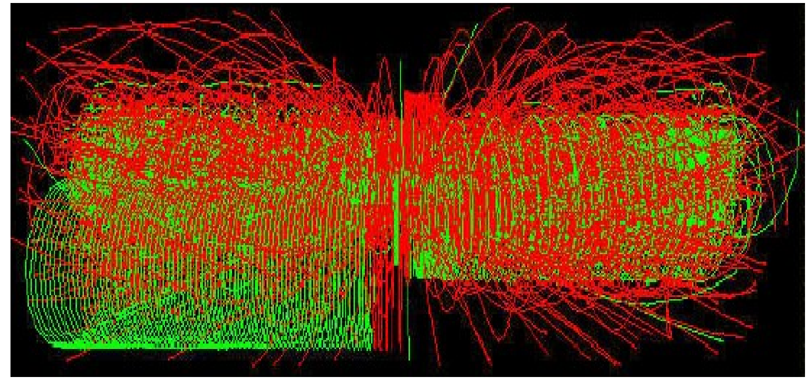
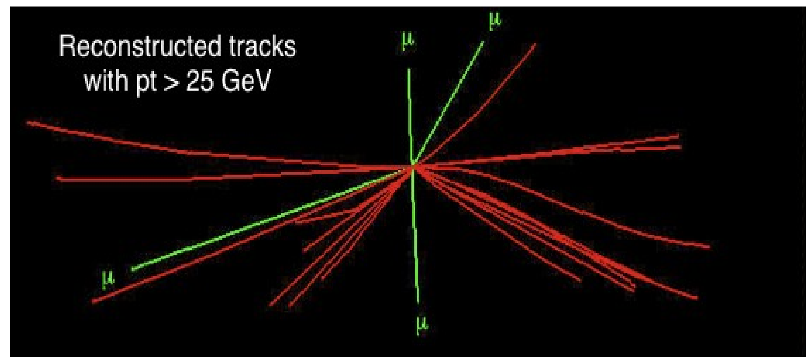
“Typical event”

H -> Z0Z0 -> 4μ





Prepare an “event – TOC”

- Data must be available fast (I.e. shortly after the interaction)
  - Some sub-detectors are build for triggering purposes
- Prepare data with low resolution and low latency in sub-detectors

Therefore for ATLAS and CMS:

- Use only calorimeter and muon data

Track reconstruction for trigger would have been too complex with available technology.

But there are upgrade plans…

First Level Trigger of ATLAS and CMS

Triggering at LHC

- **The trigger dilemma:**
  - Achieve **highest efficiency for interesting events**
  - Keep **trigger rate as low as possible (high purity)**
    - Most of the interactions (called minimum bias events) are not interesting
    - DAQ system has limited capacity

- **Need to study event properties**
  - Find differences between minimum bias events and interesting events
  - Use these to do the trigger selection

Triggering wrongly is dangerous:

Once you throw away data in the 1st level trigger, it is lost for ever

- Offline you can only study events which the trigger has accepted!
- Important: must determine the trigger efficiency (which enters in the formulas for the physics quantities you want to measure)
- A small rate of events is taken "at random" in order to verify the trigger algorithms ("what would the trigger have done with this event")
- Redundancy in the trigger system is used to measure inefficiencies

Boundary conditions for level 1

- **Max trigger rate**
  - DAQ systems of CMS/ATLAS designed for approx. **100 kHz**
  - Assumes average event size of **1-1.5 MB**.

  - Trigger rate estimation
  - Difficult task since depends on lots of unknown quantities:
    - Physics processes are not known at this energy (extrapolation from lower energy experiments)
    - Beam quality
    - Noise conditions

- **Trigger was designed to fire with ≈ 35 kHz**
  - Security margin 3 for unforeseen situations like noise, dirty beam conditions, unexpected detector behavior

- **Trigger design needs to be flexible**
  - need many handles to adjust the rates.

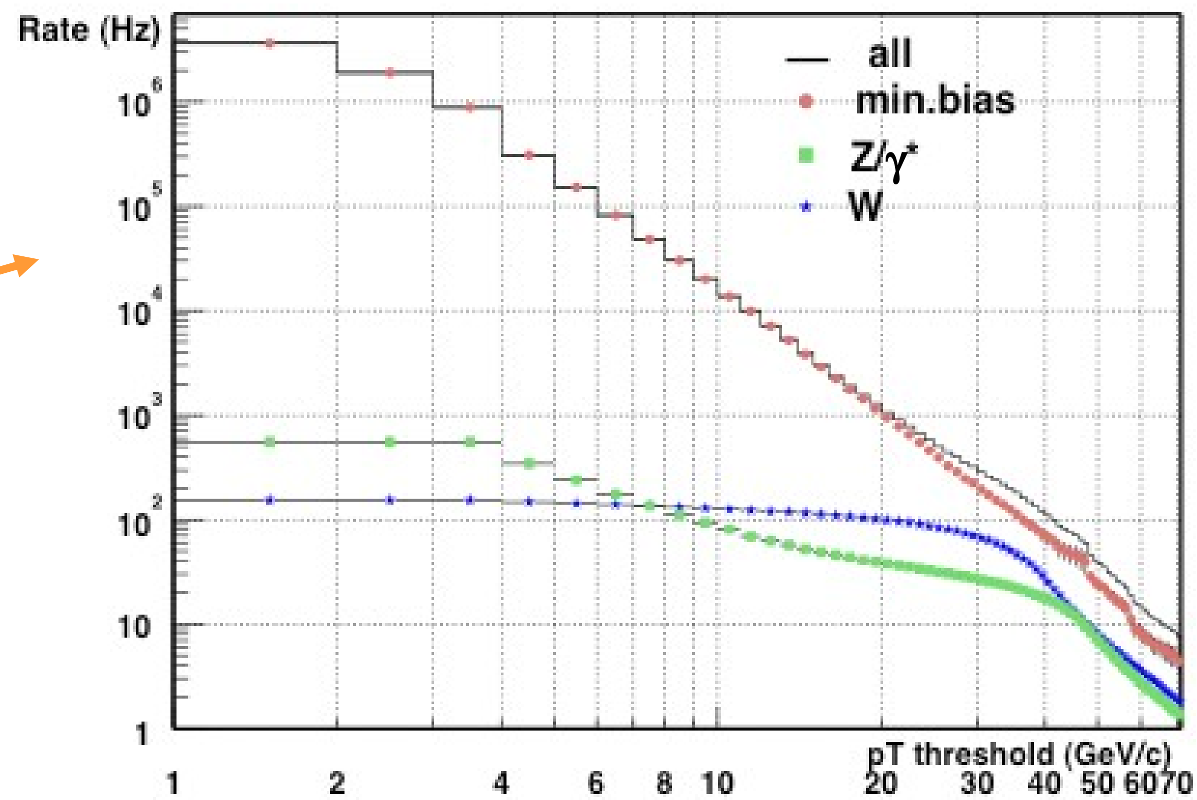
Triggering at LHC : example Muons

- **Minimum bias events in pp:**
  - Minimum bias: decays of quarks e.g. pions (SM)
- **“Interesting” events**
  - Often W/Z as decay products

Example: single muons min. bias vs W/Z decays

Threshold ≈ 10 GeV
Rate ≈ 20 kHz

$L = 10^{34}$



Cont'ed: triggering on Muons

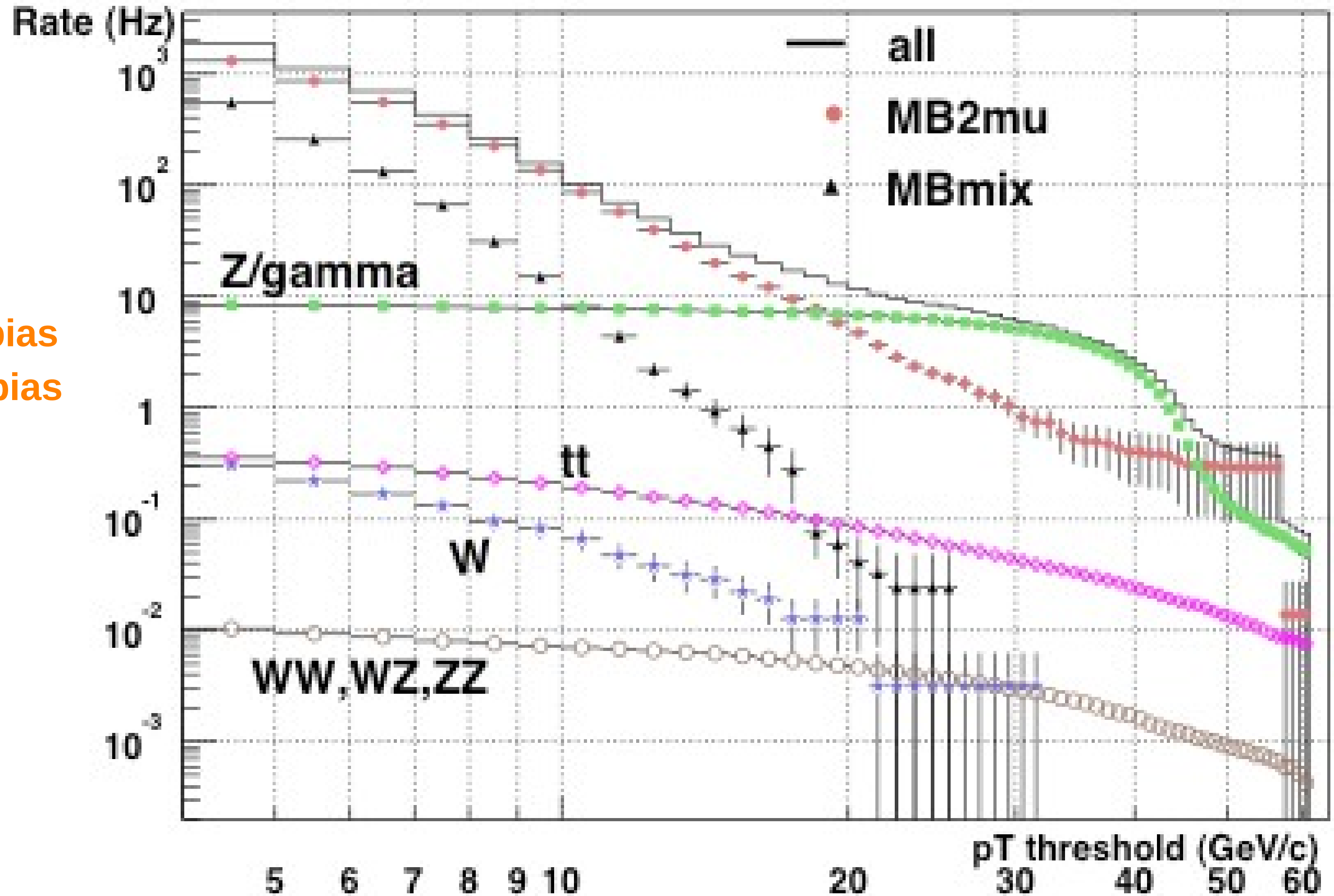
- **Interesting events: contains (almost) always 2 objects to trigger on**

Example muon pairs :

MB2mu : 2μ from min bias
Mbmix : 1μ from min bias

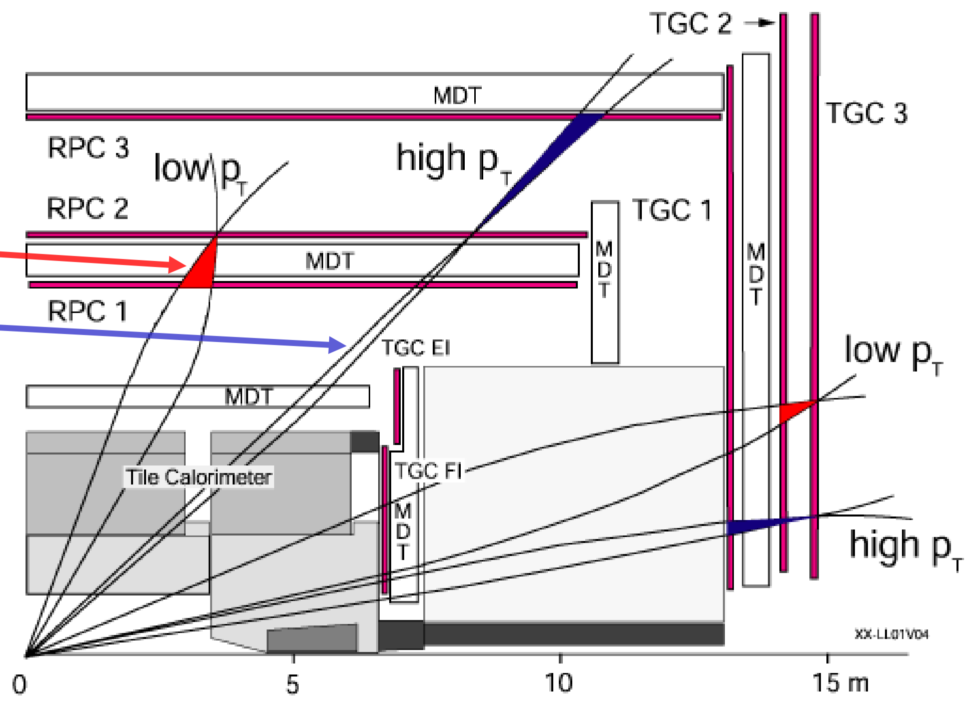
Threshold ≈ 10 GeV
Rate ≈ 100Hz

L = 10^{34}



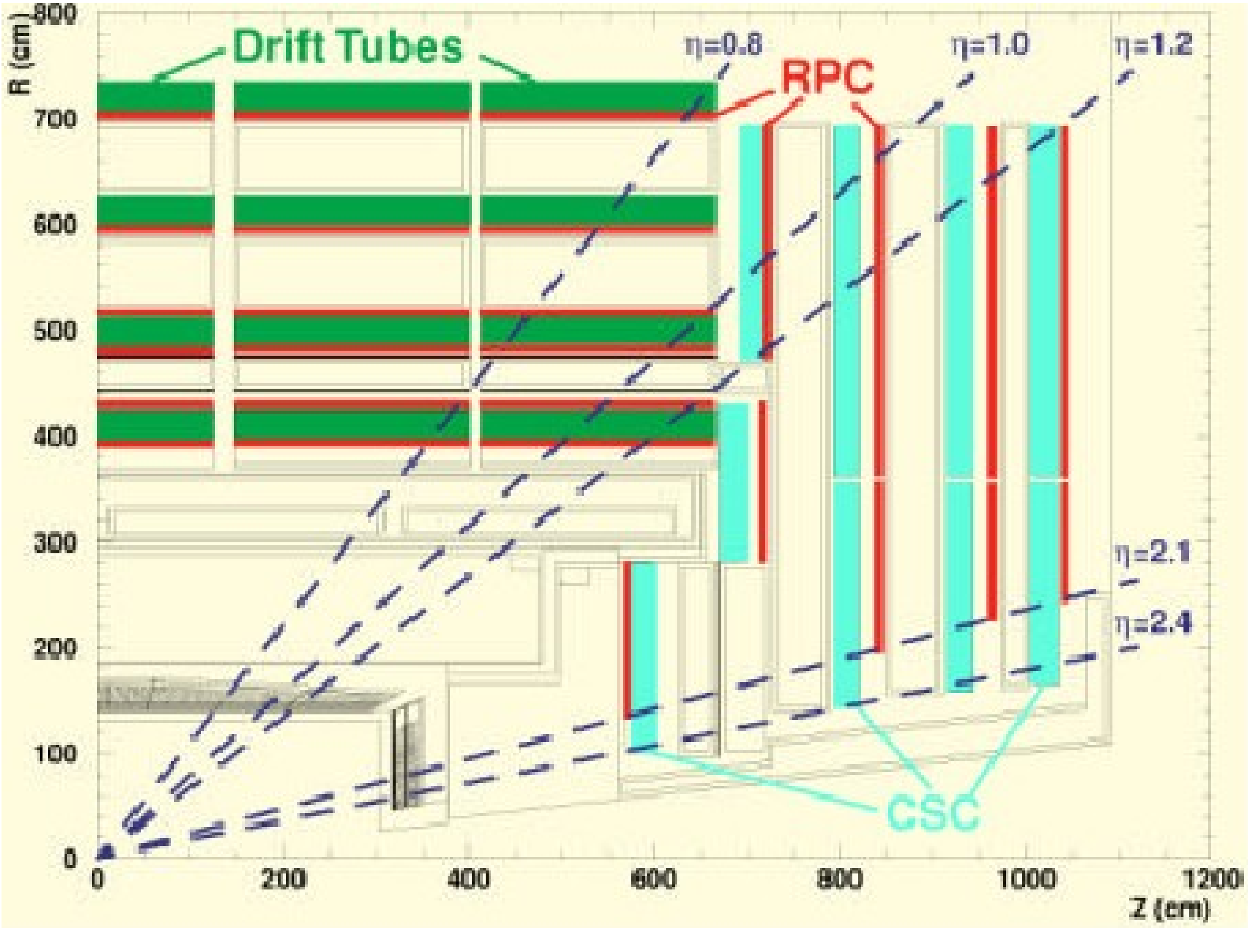
How to trigger on Muons

- **Example ATLAS muon trigger**
  - Three muon detectors:
    - Muon Drift Tubes (MDT) : high precision, too slow for level 1 trigger
    - Resistive Plate Chambers (RPC) : 1st level trigger barrel
    - Thin Gap Chambers (TGC) : 1st level trigger endcap
  - **Measure p_t** by forming coincidences in various layers:
    - Low p_t : 2 layers
    - High p_t: 3 layers
  - "**Coincidence matrix**"
    - Implemented with ASIC (Application Specific Integrated Circuit)

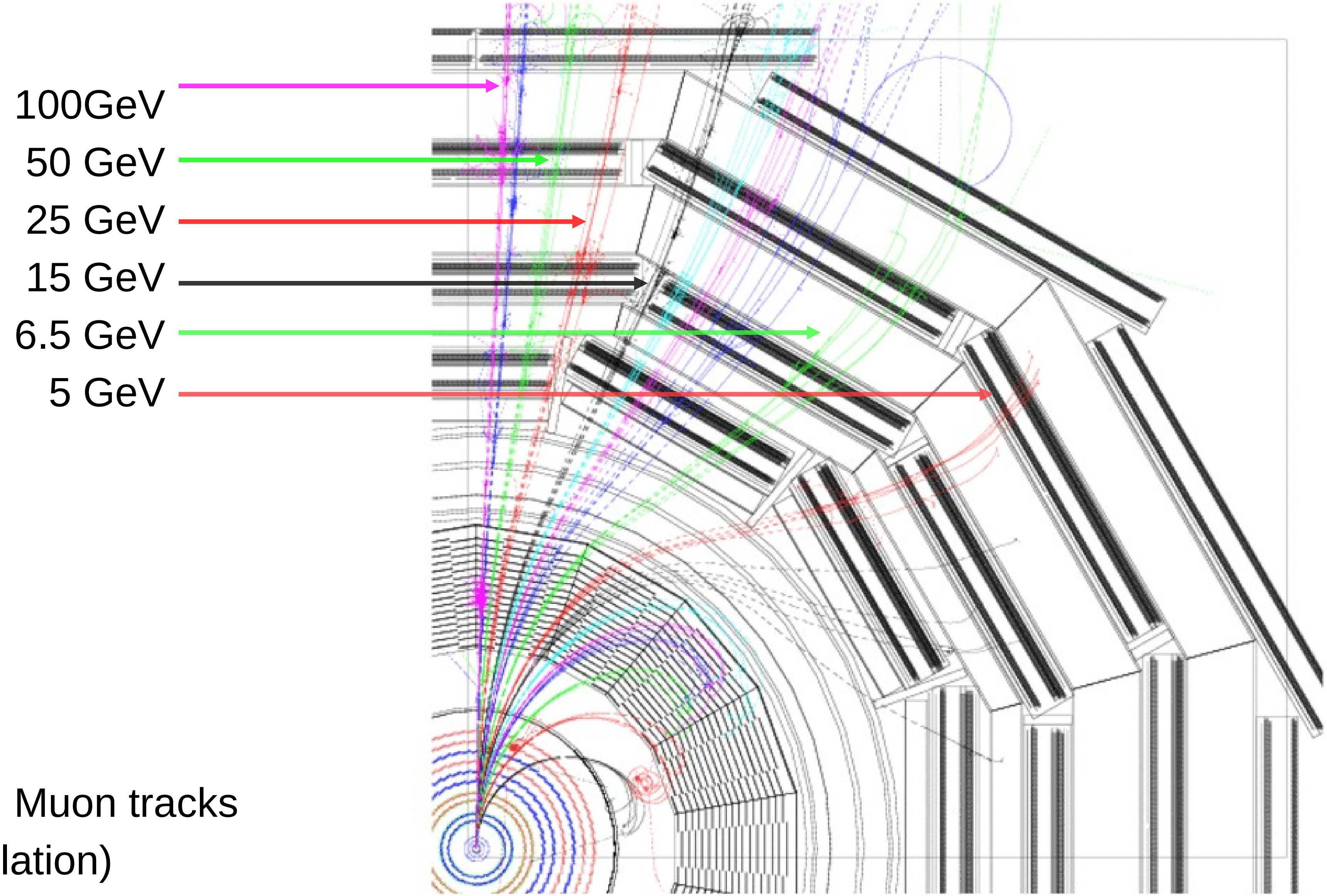


How to trigger on Muons

The CMS muon system



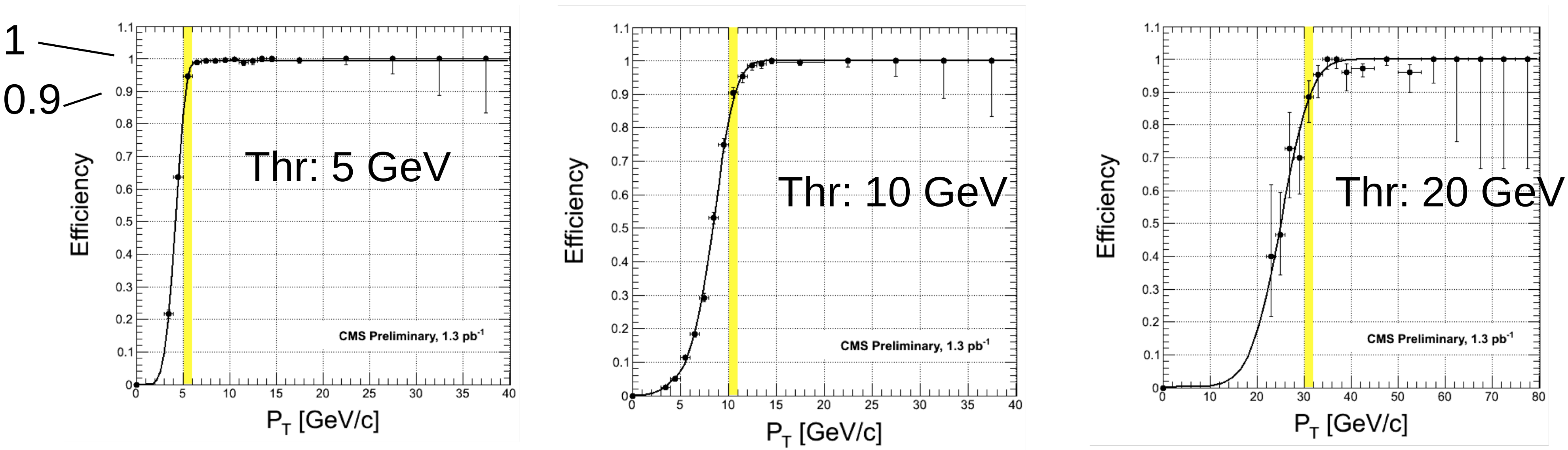
How good does it work?



CMS: Muon tracks
(simulation)

Performance of CMS muon trigger

- **Efficiency turn-on curves**

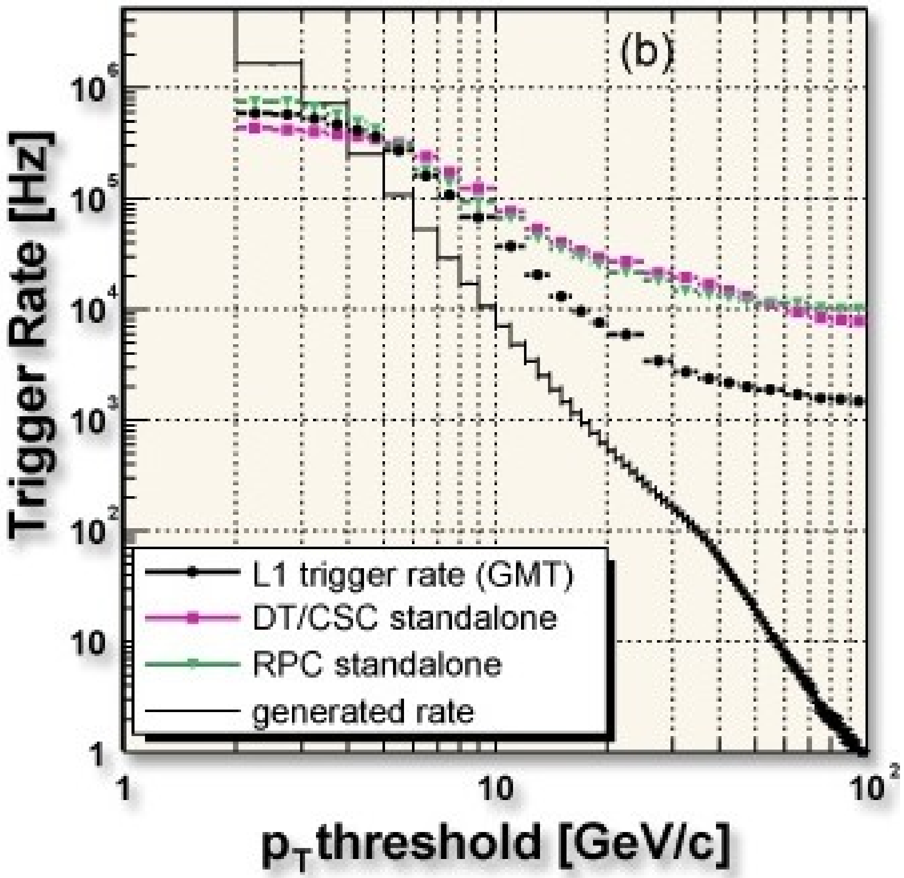


  - From Data with events: J/ψ → μμ and Z → μμ
  - “Real” pt vs. efficiency for imposed trigger threshold
  - For an imposed threshold x the efficiency for muons with pt = x GeV is larger 90% (…as foreseen).

Redundancy in the CMS Muon trigger

Generated Muons versus trigger rate (simulation)

L = 10^34



Redundancy allows to impose tight quality cuts (i.e. number of hits required for each muon, …)

this improves purity

p_t > 20GeV:

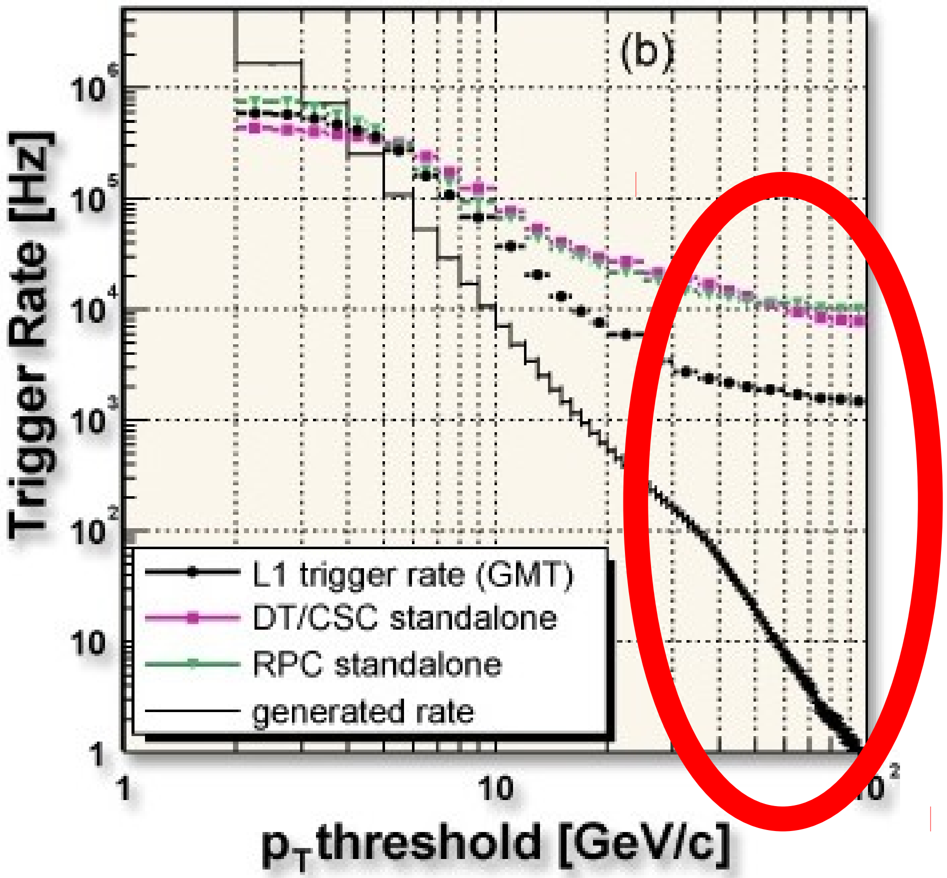
≈ 600 Hz generated,

≈ 8 kHz trigger rate

But: Let's have a closer look...

Generated Muons versus trigger rate (simulation)

$L = 10^{34}$



Trigger rate stays high even when thresholds is increased !!!

Why??? - Low Pt muons are mis-identified (There are a LOT of low pt particles in the forward region)

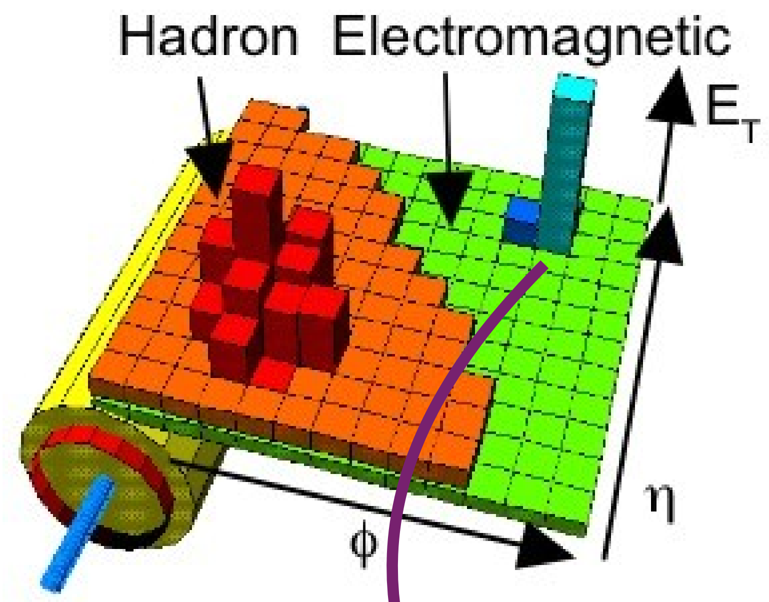
Problem for Lumi > n x 10^{34}

UPGRADE:

Finer granularity in forward region and additional chambers: less mis-identification

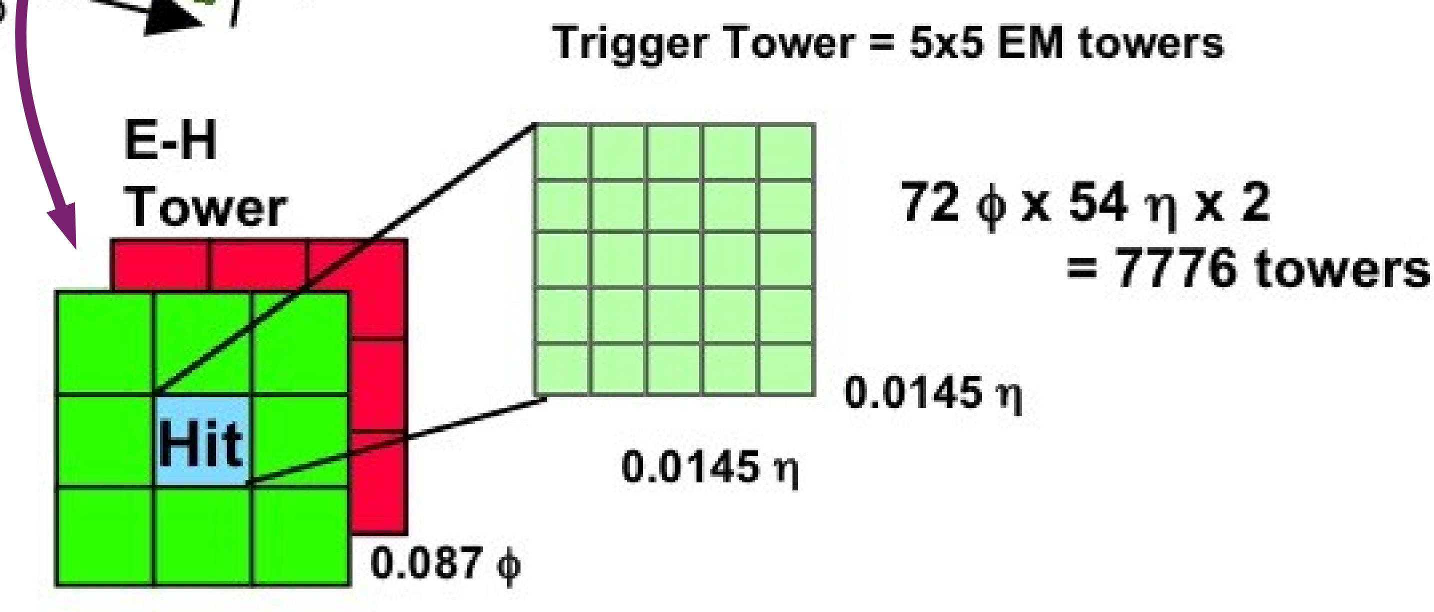
New Trigger Logic (see later)

Calorimeter Trigger: example CMS



Divide Calorimeter into towers

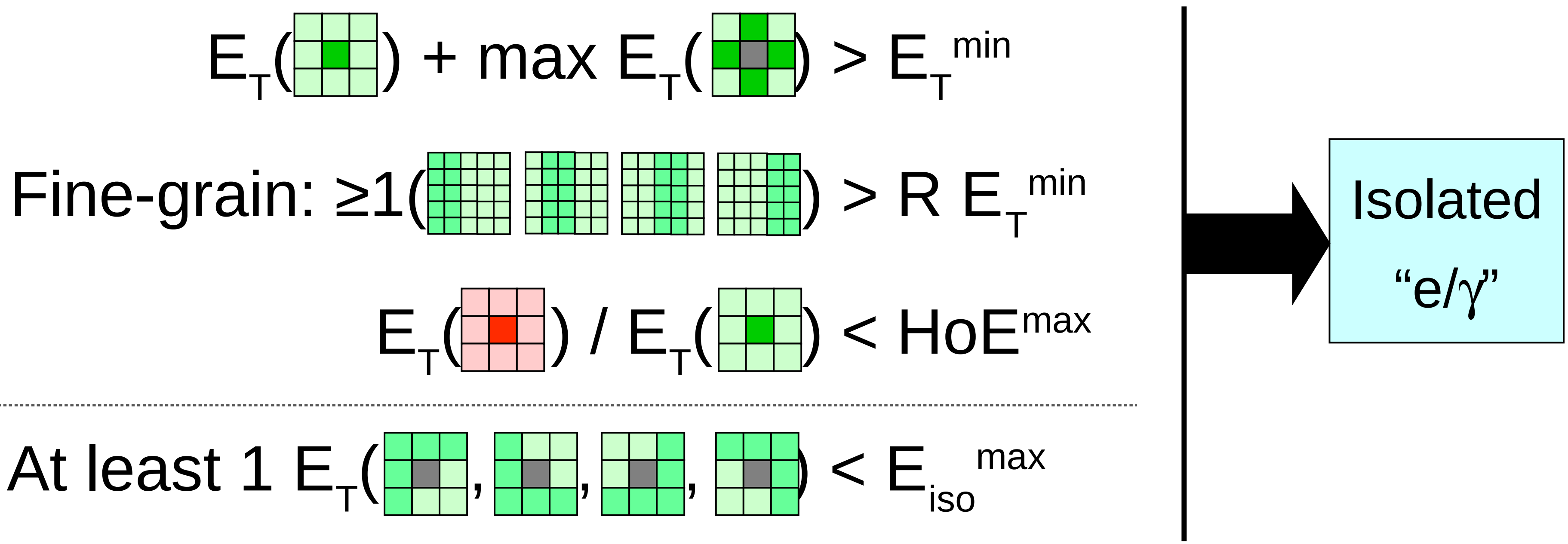
Match towers between ECAL and HCAL



Algorithm to identify e/γ

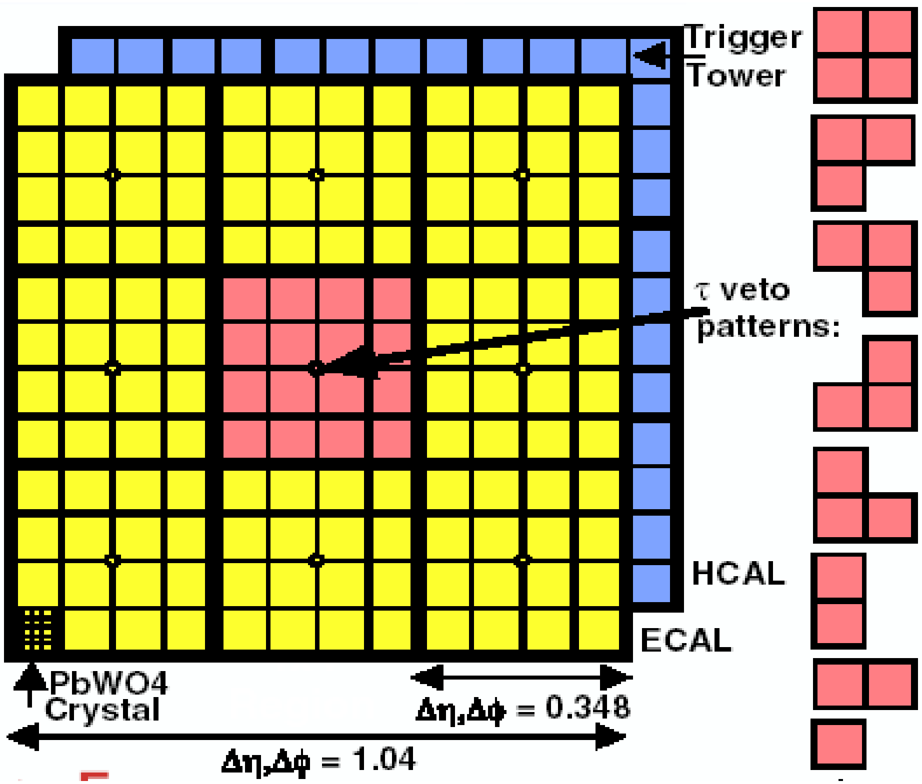
Characteristics of isolated e/γ:

- energy is locally concentrated (opposed to jets)
- energy is located in **ECAL**, not in **HCAL**



Calorimeter Trigger: jets and Taus

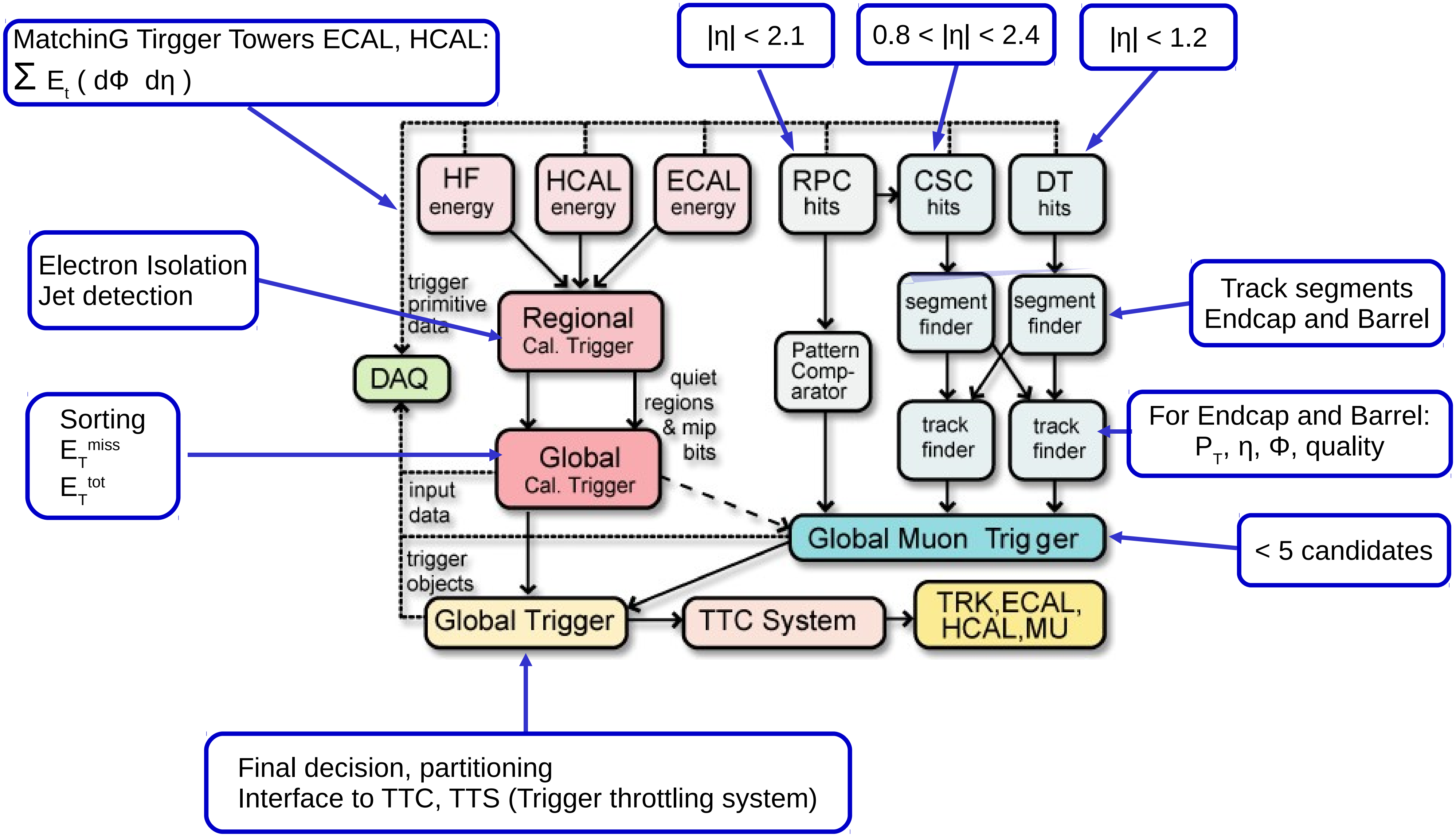
- **Algorithms to trigger on jets and tau:**
  - based on clusters 4x4 towers
  - Sliding window of 3x3 clusters



- **Jet trigger : work in large 3x3 region:**
  - $E_t^{central} > E_T^{threshold}$
  - $E_t^{central} > E_T^{neighbours}$

- **Tau trigger: work first in 4x4 regions**
  - Find localized small jets:
    If energy not confined in 2x2 tower pattern -> set Tau veto
  - Tau trigger: No Tau veto in all 9 clusters

Trigger Architecture: CMS



Global Trigger

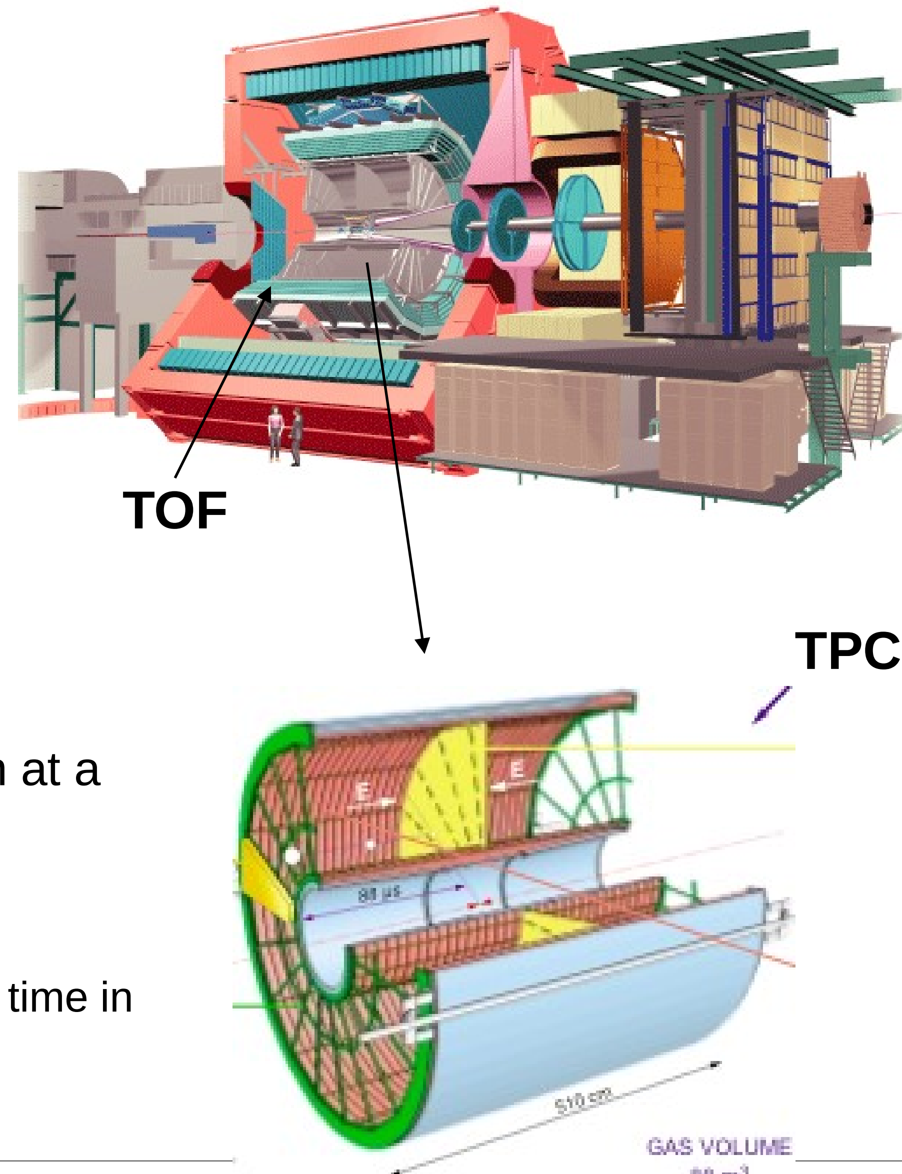
- **Forms final decision**
  - Programmable "Trigger Menu"
  - Logical "OR" of various trigger conditions
    - In Jargon these trigger conditions are called "triggers" themselves. The individual triggers may be downscaled (only take every 5th) Example:

1 μ	with Et > 20 GeV	**or**	"single muon trigger"
2 μ	with Et > 6 GeV	**or**	"di - muon trigger"
1 e/γ	with Et > 25 GeV	**or**	"single electron trigger"
2 e/γ	with Et > 15 GeV	**or**	"di - electron trigger"
	⋮		

Specific solutions for specific needs: ALICE and LHCb

ALICE: 3 hardware trigger levels

- **Some sub-detectors e.g. TOF (Time Of Flight) need very early strobe (1.2 µs after interaction)**
  - Not all subdetectors can deliver trigger signals so fast
  - Split 1st level trigger into :
  - **L0 : latency 1.2 µs**
  - **L1 : latency 6.5 µs**



- **ALICE uses a TPC for tracking**
  - TPC drift time: **88µs**
  - In Pb-Pb collisions only one interaction at a time can be tolerated (otherwise: too many tracks in TPC)
  - Need **pile-up protection**:
    - Makes sure there is only one event at time in TPC (need to wait for TPC drift time)
  - **L2 : latency 88µs**

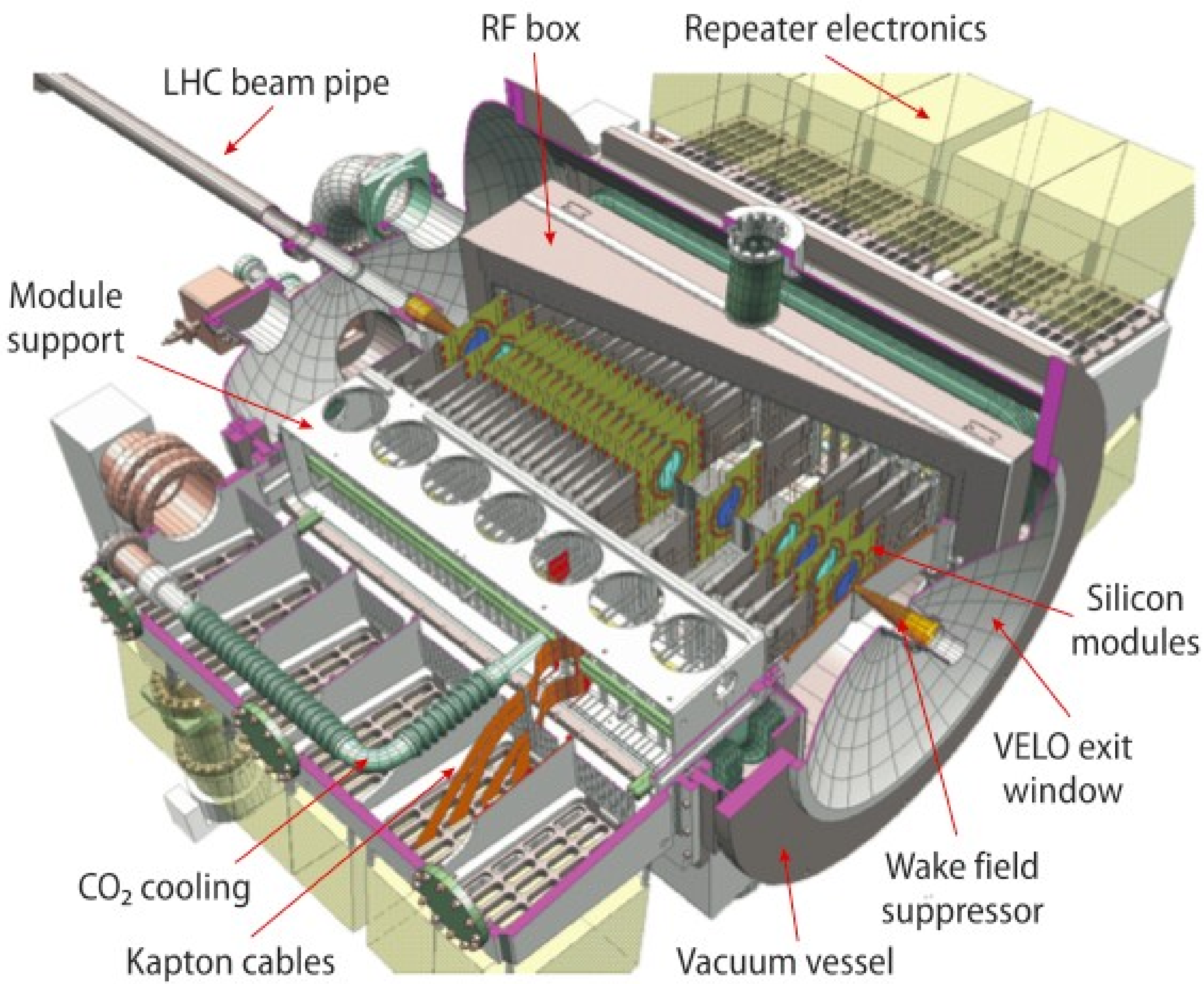
ALICE: optimizing efficiency

- **Specific property of ALICE:**
  - Some sub-detectors need a long time to be read out after LVL2 trigger (e.g. Si drift detector: 260μs)
  - But: Some interesting physics events need only a subset of detectors to be read out.

- **Concept of Trigger clusters:**
  - Trigger cluster: group of sub-detectors
    - one sub-detector can be member of several clusters
  - Every trigger is associated to one Trigger Clusters
  - Even if some sub-detectors are busy due to readout: triggers for not-busy clusters can be accepted.

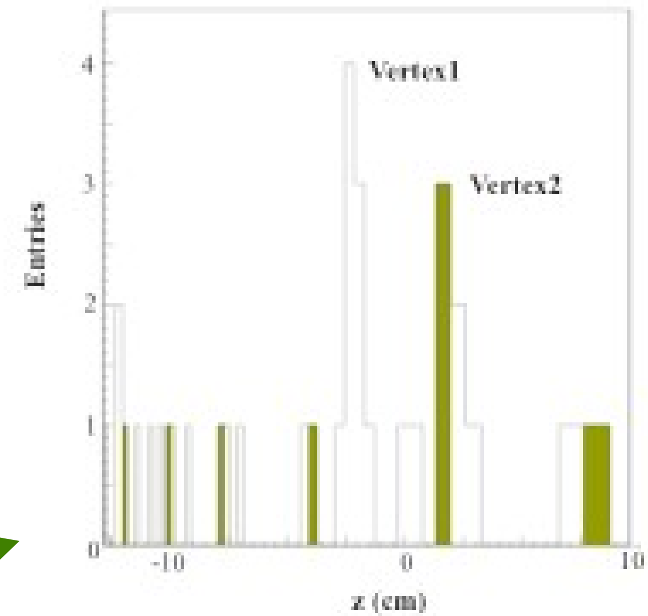
- **Triggers with “rare” classification:**
  - In general at LHC: stop the trigger if readout buffer almost full
  - ALICE:
    - “rare” triggers fire rarely and contain potentially interesting events.
    - when buffers get “almost-full” accept only “rare” triggers

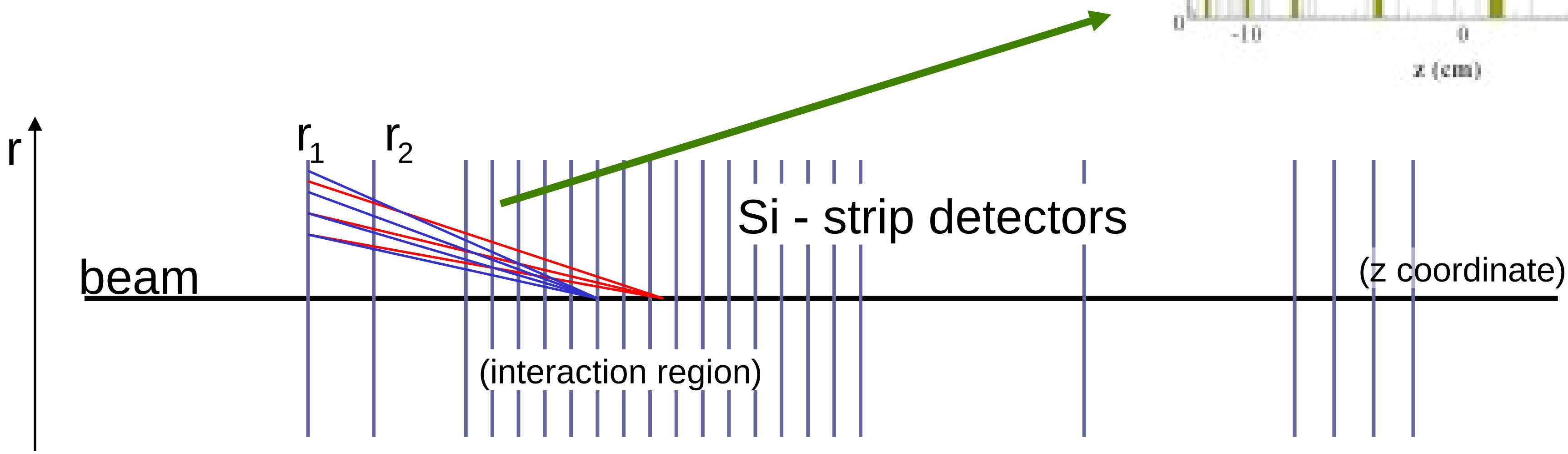
LHCb: VELO (Vertex Locator)



LHCb: pile-up protection

- **LHCb needs to identify displaced vertices online**
  - This is done in the HLT trigger (see later)
  - This algorithm only works efficiently if there is no pile-up (only one interaction per BX)
  - Pile-up veto implemented with silicon detector: Detect multiple PRIMARY vertices in the opposite hemisphere



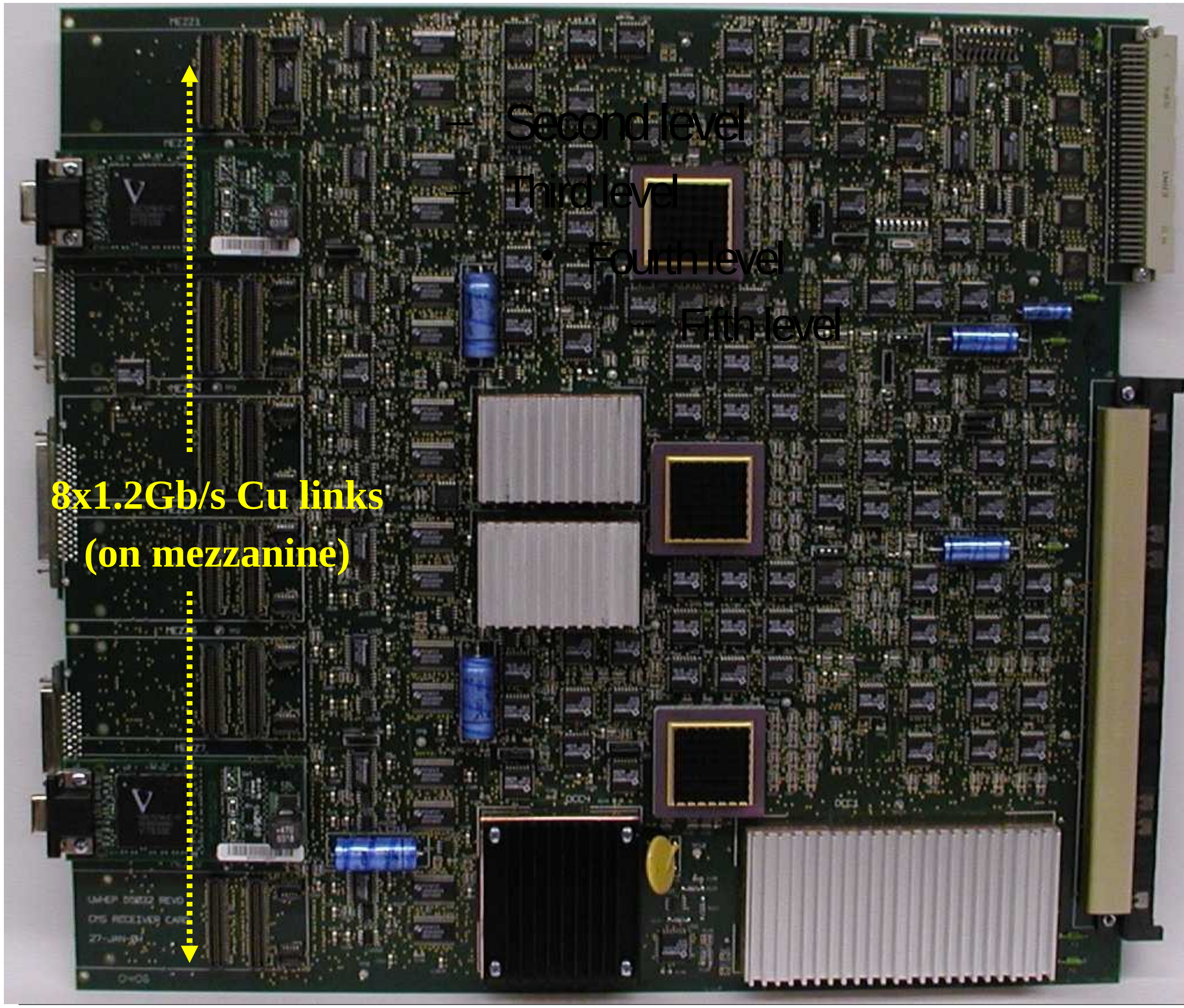


Trigger implementation

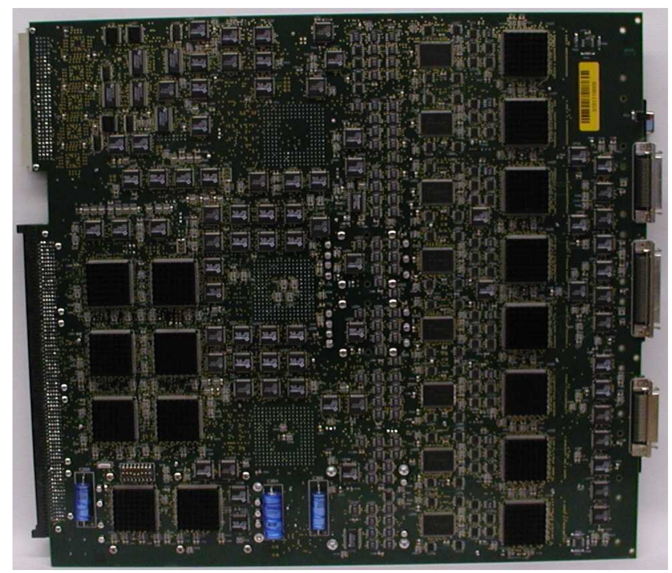
CMS: Regional Calorimeter Trigger

Receives 64 Trigger primitives from (32 ECAL, 32 HCAL)

Forms two 4x4 Towers for Jet Trigger and 16 ET towers for electron identification card



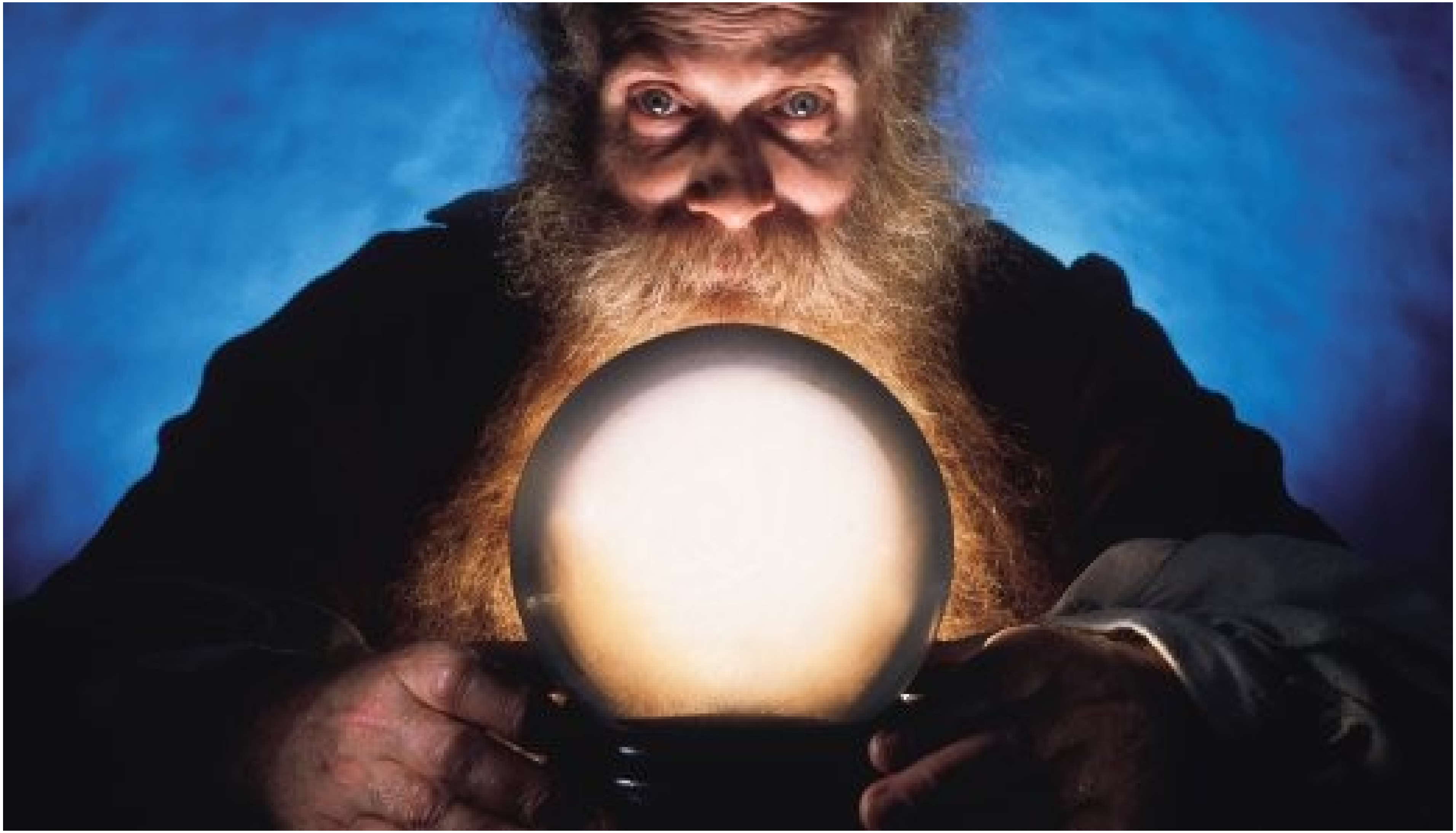
“solder” - side of the same card:



Trg. Implementation: Interconnectivity

You might guess that todays modern technology (serial links, uTCA,…) offers some room for improvement in a future upgrade project…

??? What does the future bring us ???



Trigger upgrades: Introduction

- **LHC plans to upgrade the accelerator in the next 2 years**

  – Energy will go from 8 TeV to 13 TeV
  – Peak Luminosity from $7x10^{33}$ to approx. $2x10^{34}$
  – Not yet clear if 25ns or 50ns bunch spacing
    - Remember the relation between this and Pileup

  – **Pileup might increase to values of 40-50**
    - The experiments were constructed for a pileup around 23

BX spacing [ns]	Beam current [$x10^{11}$ e]	Emittance [µm]	Peak Lumi [x $10^{34}cm^{-2}s^{-1}$]	Pileup
25	1.15	3.5	0.92	21
25	1.15	1.9	1.6	43
50	1.6	2.3	0.9-1.7	40-76
50	1.6	1.6	2.2	108

Trigger updates: Introduction

- **The high pileup degrades the performance of current trigger algorithms**
  - If nothing is done the rates exceed by far 100 kHz

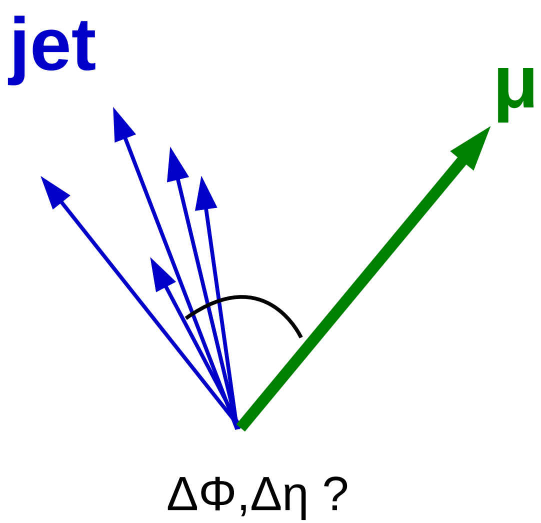
- **The Higgs boson is relatively light (125 GeV)**
  - The future physics program foresees to investigate this boson with enhanced precision.
    - This means trigger **efficiencies need to stay** at least as good as they are.
    - **Trigger thresholds cannot be increased** without “cutting into the physics”

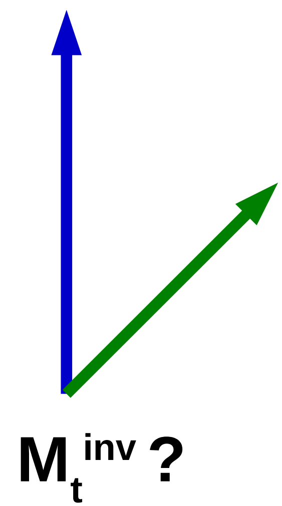
- **The experiments need to find ways to**
  cope with the higher pileup without loosing efficiency for physics

- **General solutions:**
  - Increase resolution for trigger object: Energy, Momentum, Spacial
    - Finer grain input data to trigger
      - More input data to the trigger
      - Enhance detectors in critical high multiplicity regions (forward region)
  - More complex algorithms
    - To be implemented in modern FPGAs
    - e.g. topological triggers, calculation of invariant mass, subtraction of pileup, ...
  - Include tracking in Lvl1 Trigger

Atlas Trigger Upgrade

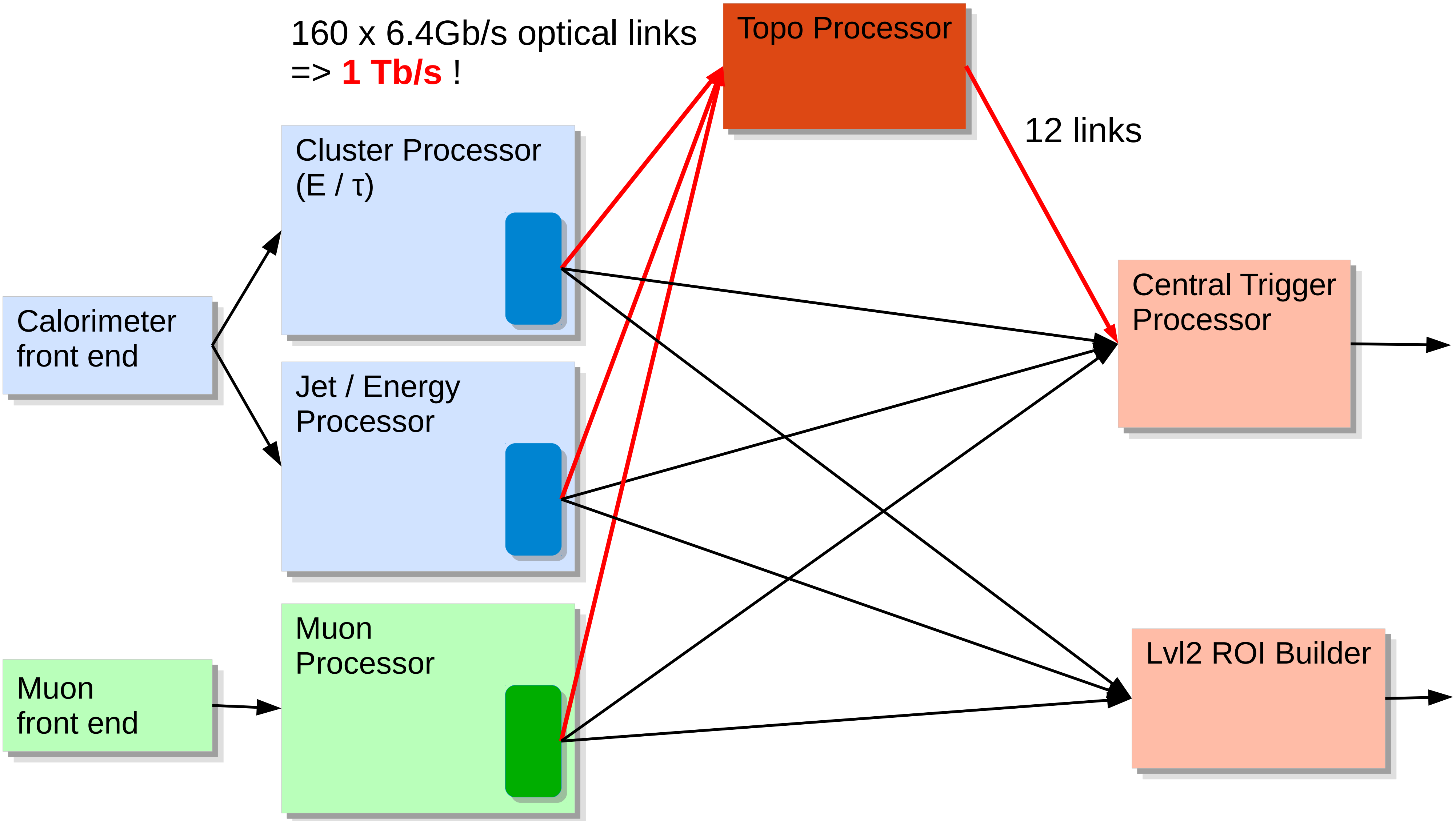
- **Keep trigger rates under control by using topology**
  - Use Trigger primitives of Lvl2: ROIs
  - Send them to dedicate topology processor based on powerful FPGAs
  - Calculate invariant masses, determine topologies like “back to back”, measure rapidity gaps, ...





Need to process topological information at Lvl1

Topological Trigger: Concept



Atlas Topological Trigger

- **Nothing comes for free...: Latency**
  - Front-end pipelines are expensive resources: **Latency budget is tight**.
  - The Topology Processor is an **additional Processing Step** in Front of the Central Trigger Processor: It “eats” from the Latency Budget.

- **ATLAS has some latency contingency**
  - Around **12 BC** contingency in the L1 latency budget can be used for the topology processor
    - This limits the complexity and number of calculations which can be done

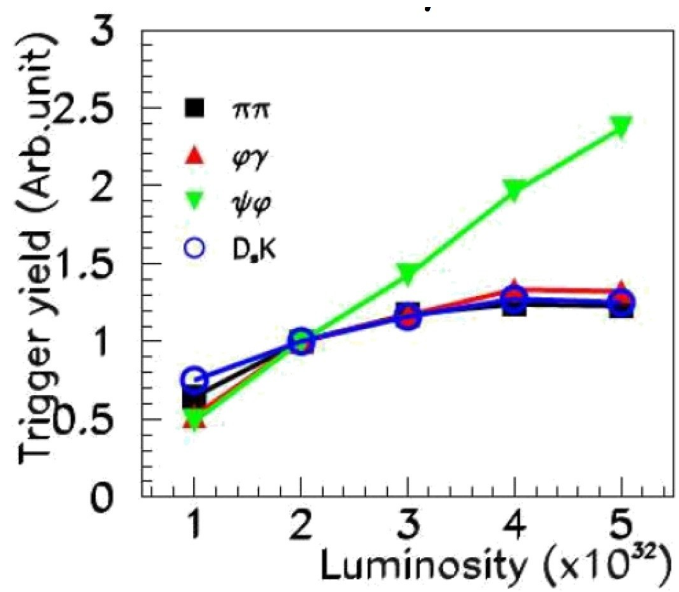
Does it make sense to upgrade LHCb ?

- **LHCb is a high statistics experiment**
  - LHCb is doing high precision measurements which are limited by statistics
  - To significantly improve the physics results of LHCb one should increase the statistics by a **factor of 10**

- **Where can LHCb gain a factor of 10 in statistics**
  - Currently LHCb takes data with $4x10^{32}$
    - Beams are on purpose separated a bit in LHCb to achieve reduce the Luminosity to this value
  - **Upgraded Lumi by factor of 5** to max. 20×10^{33}

Does it make sense to upgrade LHCb ?

- **Gain another factor of 2 in B → π π**
  - Currently efficiency of this channel is about 50% due to inefficiency in the first level trigger.
  - To gain back the 50% lost efficiency: plan to run without Hardware Trigger.



    - This means to construct a DAQ system with effectiv
    - Events at the luminosity of 10^{33} are expected to have 100kB
    - This results in a 30 Tb/s Event Builder!
  - As an emergency brake the Lvl0 Trigger will be kept and can be switched on.

Therefore...

Yes, it DOES make sense to upgrade LHCb

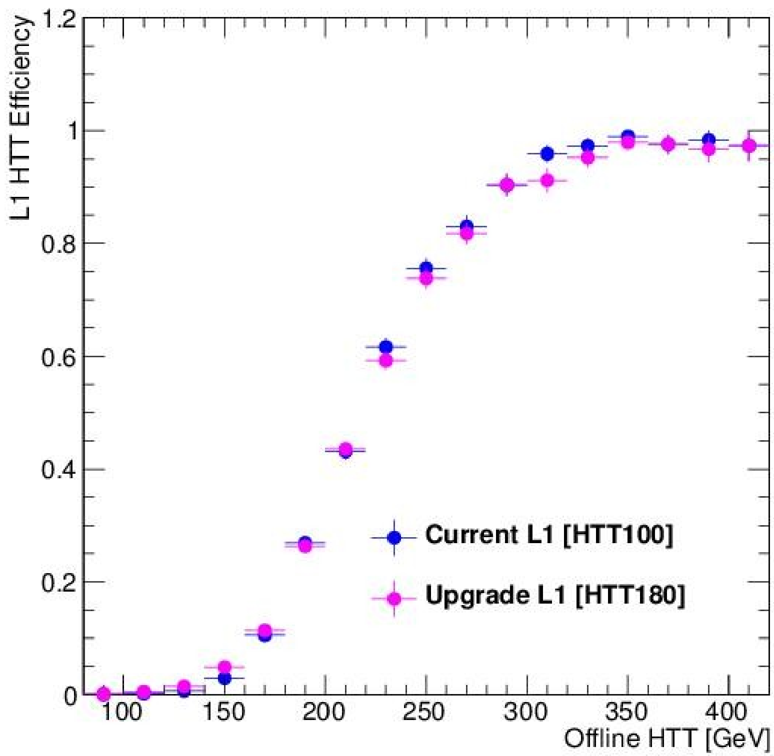
Calorimeter Trigger of CMS

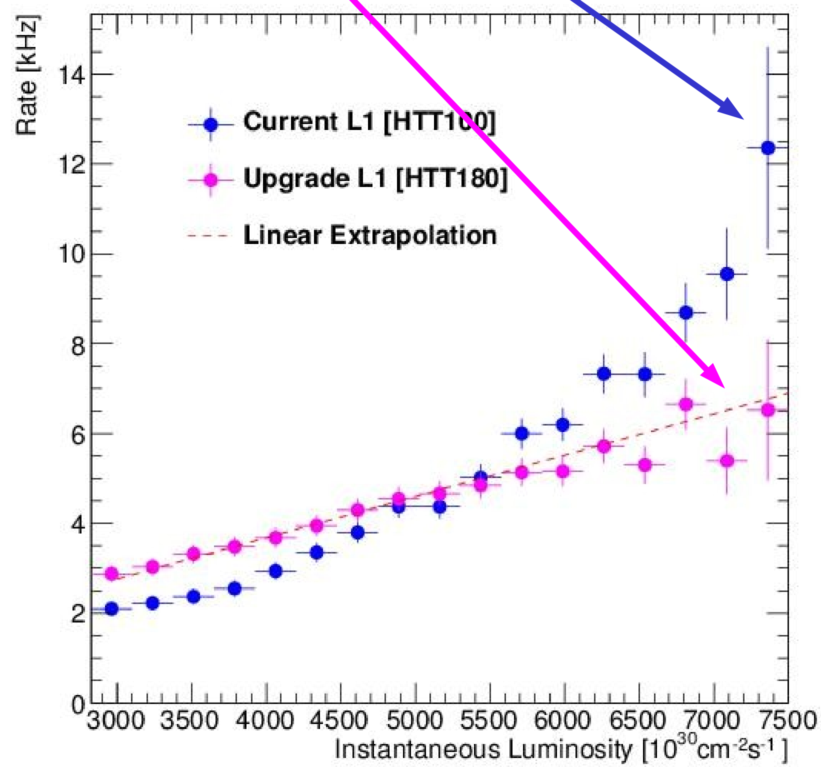
- **Upgrade of the Calorimeter Trigger electronics will bring improvements in various area**

  - Make use of full granularity of trigger primitives available.
    - (The current trigger is not able to exploit this)
  - The resulting better spacial resolution will allow to improve significantly the τ-trigger.
    - τ-triggers are based on finding small jets requiring good resolution

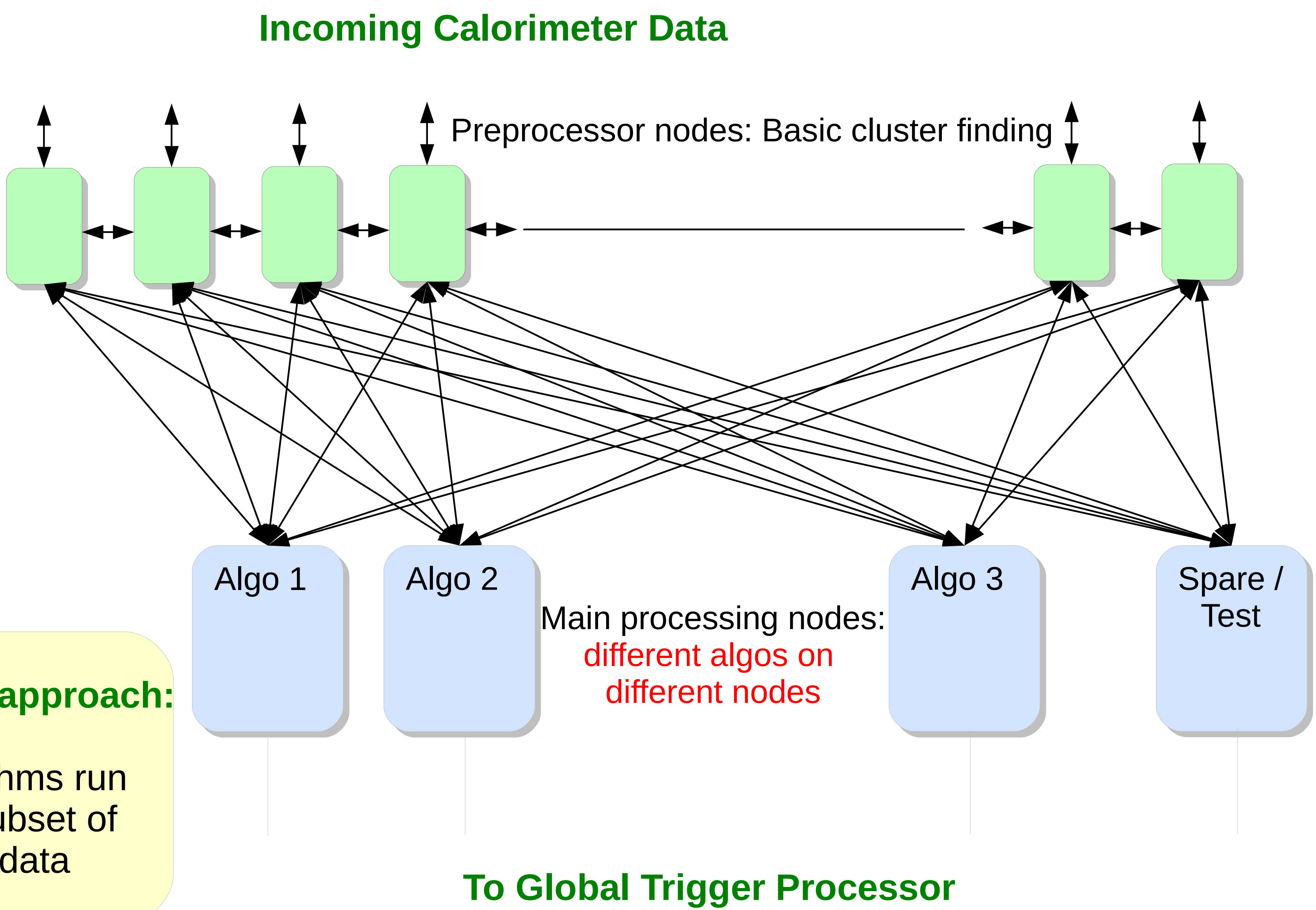
Calorimeter Trigger of CMS

- **More Complex Trigger Algos: Event by Event Pileup subtraction**
  - HTT : trigger on total transverse Jet Energy: At high pileup the rate of this trigger grows exponentially in the current system
  - With Pileup subtraction the trigger rate increases linearly with moderate slope





Upgrade of CMS Calorimeter Trigger: Variant 1

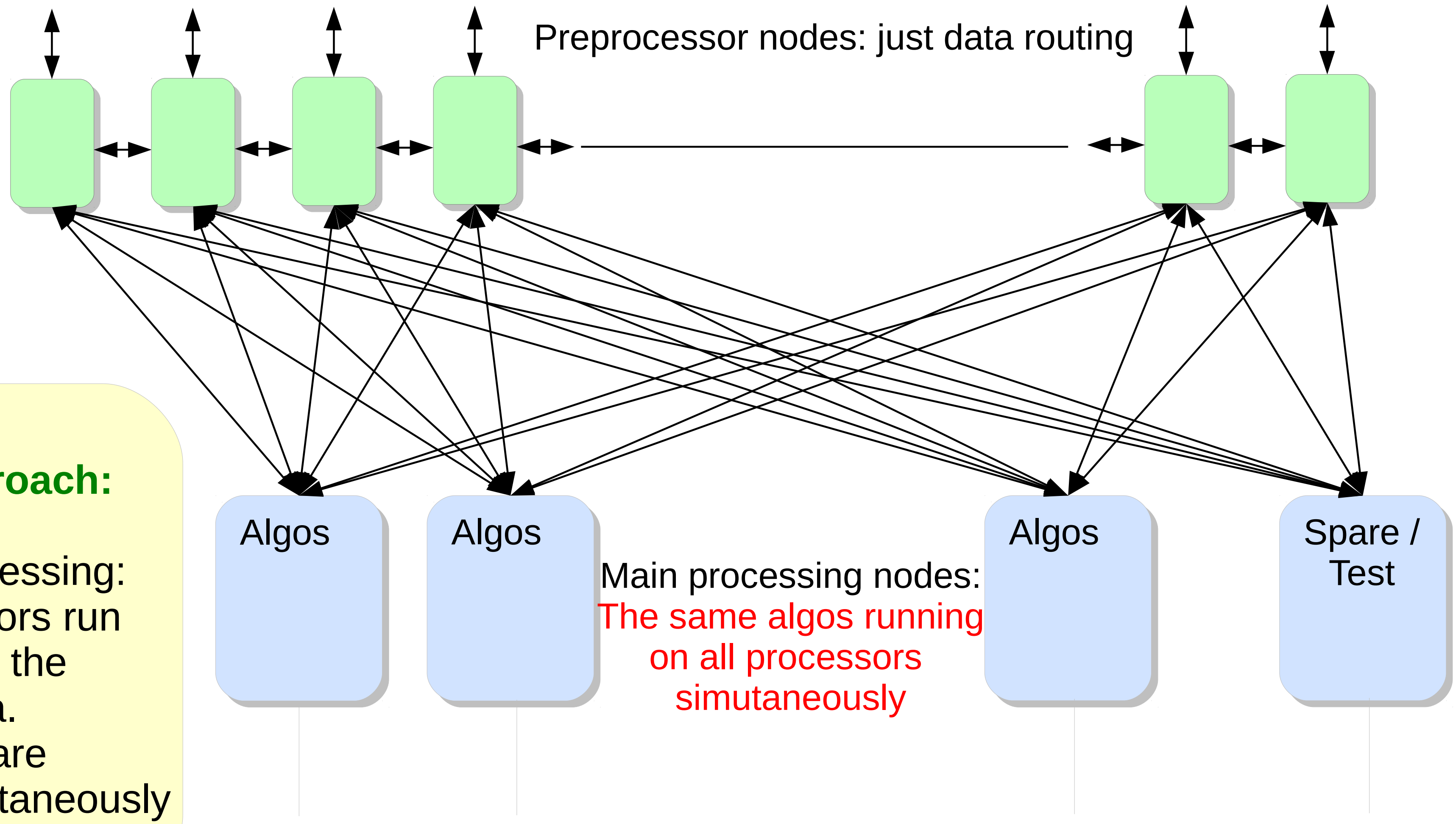


Conventional approach:

Specific Algorithms run on a specific subset of pre-processed data

CMS Calorimeter Trigger: Time Sliced

Incoming Calorimeter Data



To Global Trigger Processor

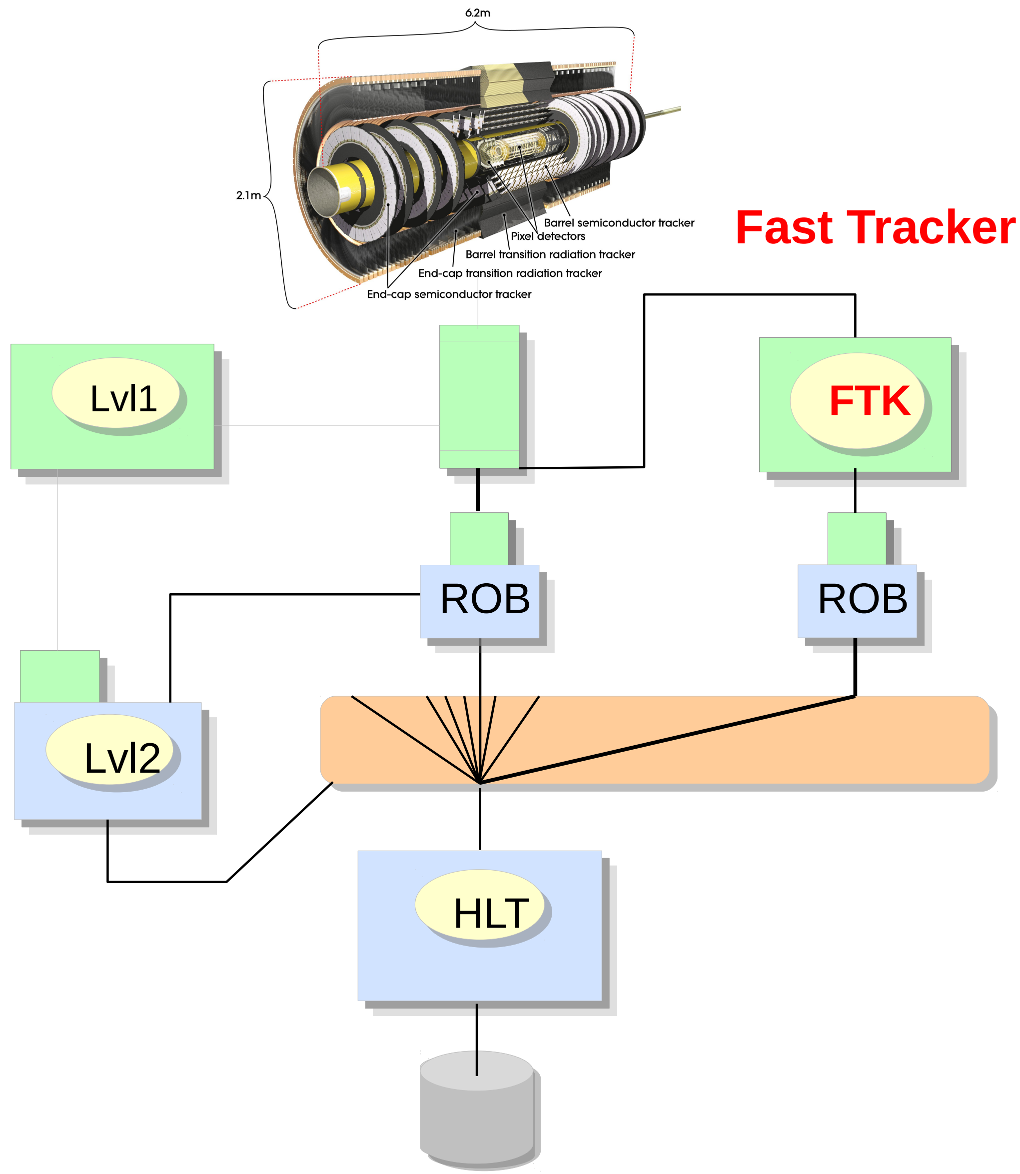
Innovative approach:

Time sliced processing:
Several processors run all algorithms on the entire event data.
Several Events are processed simultaneously

Atlas: First step to a Hw-Track Trigger

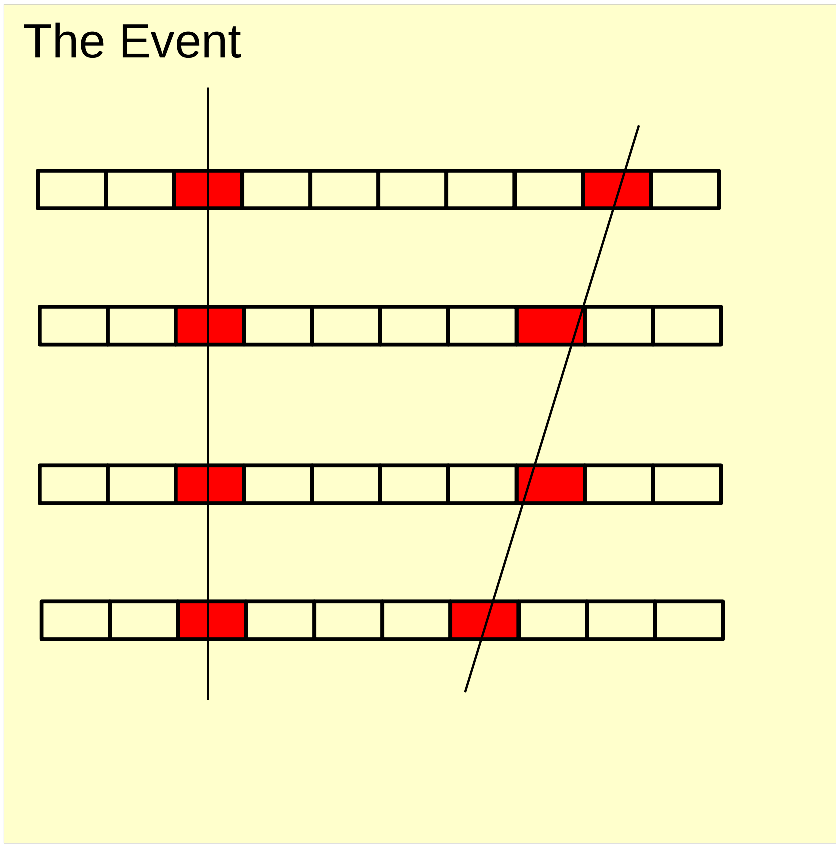
- **Track-finding is CPU intensive**
  - Especially in high pileup events the events the resources needed to do track-finding increase exponentially

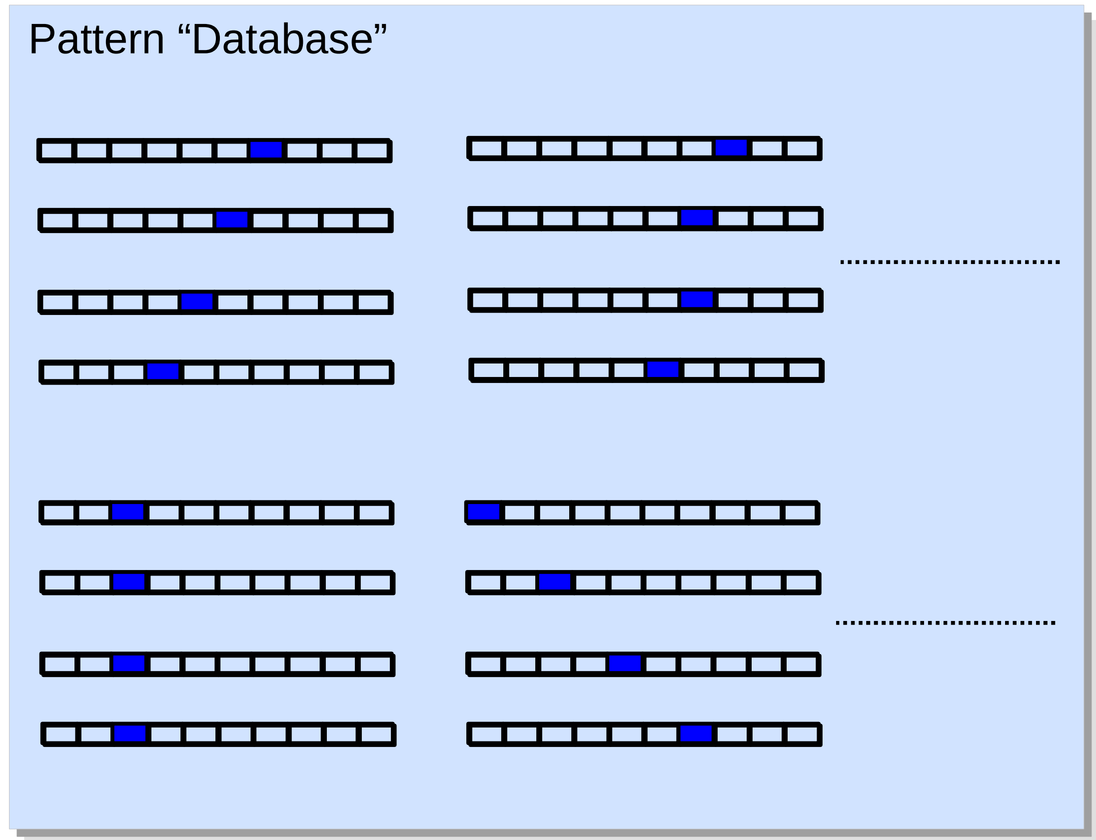
- **Idea: Special highly parallel hardware processors should find tracks**
  - The output of the processor will be available at Lvl2 / Filter
  - The CPU time saved by not having to do tracking can be used for other trigger algorithms.



How to build a Hardware Tracker

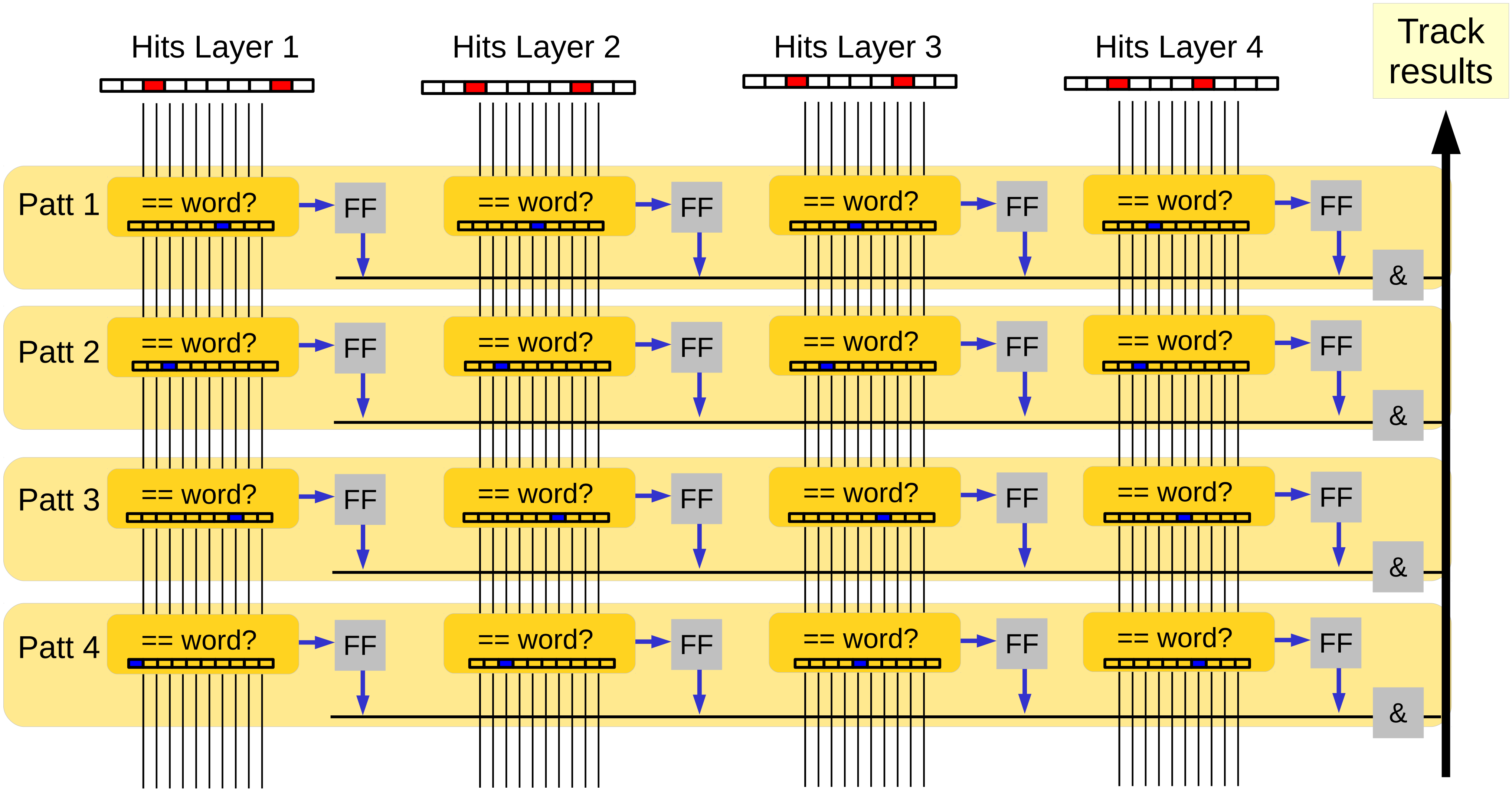
- **Compare the Event Hit Pattern with many Stored patterns**
  - The comparision with all patterns has to be done in parallel!





Implementation of Hardware Track Trigger

Principle of a CAM: Content Addressable Memory



Conclusion

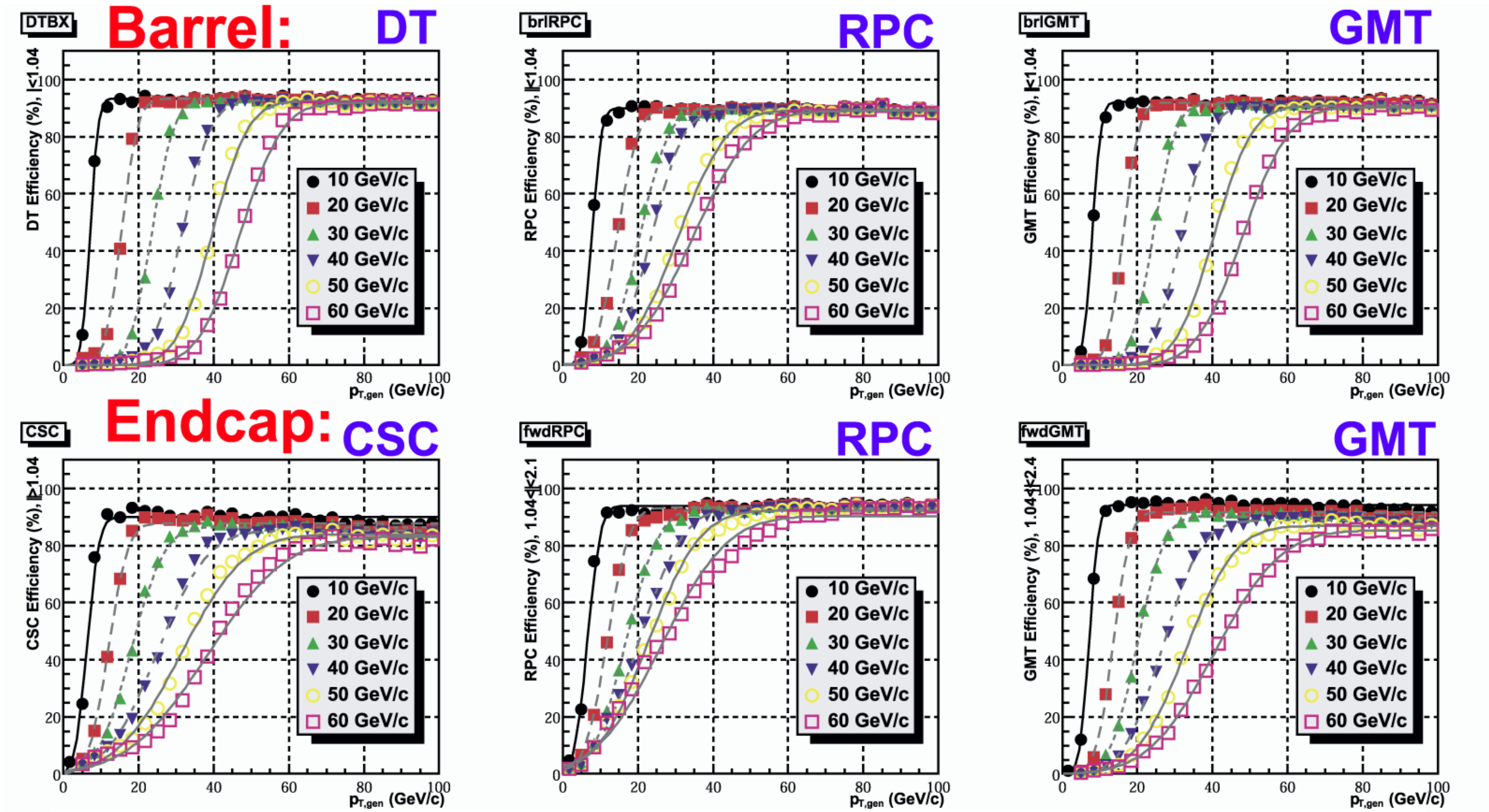
- **The concepts and techniques you learned in this school are widely applied in the LHC experiments.**

- **The design for the trigger of the LHC experiments is driven by**
  - Physics needs
  - Conditions of the accelerator
  - Compromises wrt budget

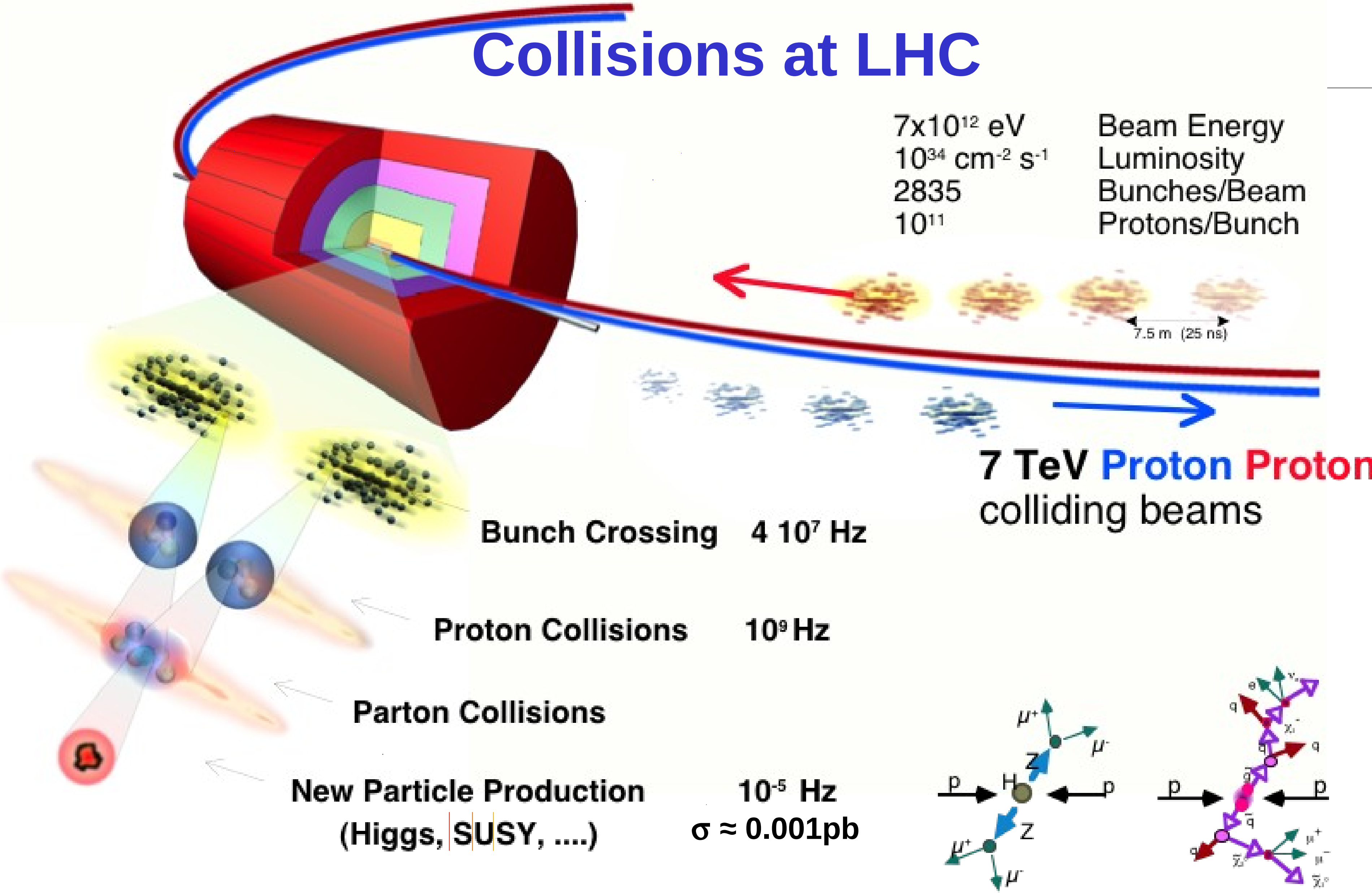
- **An exciting upgrade program has started in order to meet the experimental challenges after upgrade of the accelerator**

Extra slides: Lvl1 trigger

CMS Muon Trigger: Efficiency



Collisions at LHC



Selection of 1 event in 10,000,000,000,000

Level-1 trigger "cocktail" (low/high lumi)

Low Luminosity

Total Rate: 50 kHz
Factor 3 safety,
allocate 16 kHz

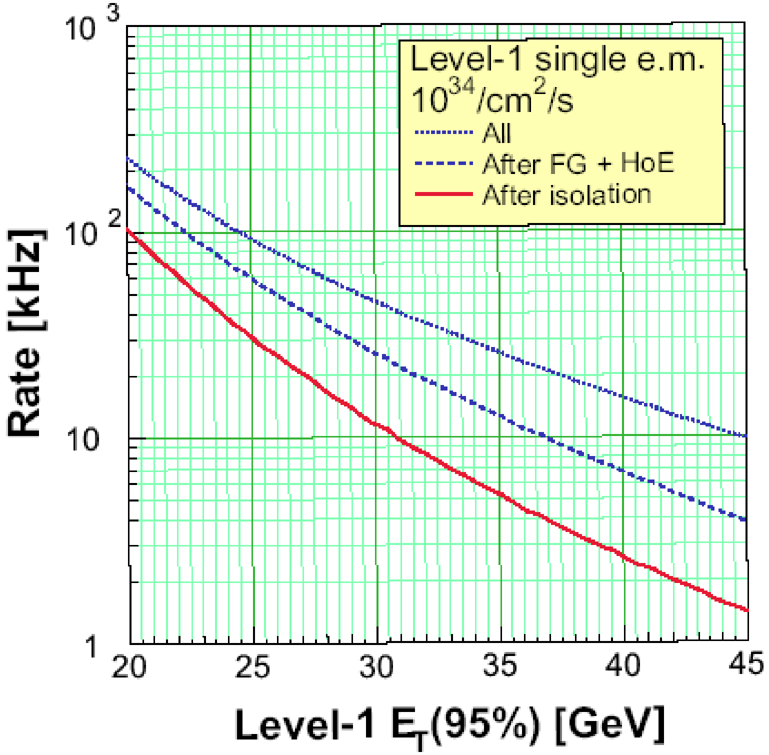
Trigger	Threshold (e=90-95%) (GeV)	Indiv. Rate (kHz)	Cumul rate(kHz)
1e/g, 2e/g	29, 17	4.3	4.3
1m, 2m	14, 3	3.6	7.9
1t, 2t	86, 59	3.2	10.9
1-jet	177	1.0	11.4
3-jets, 4-jets	86, 70	2.0	12.5
Jet & Miss-ET	88 & 46	2.3	14.3
e & jet	21 & 45	0.8	15.1
Min-bias		0.9	16.0

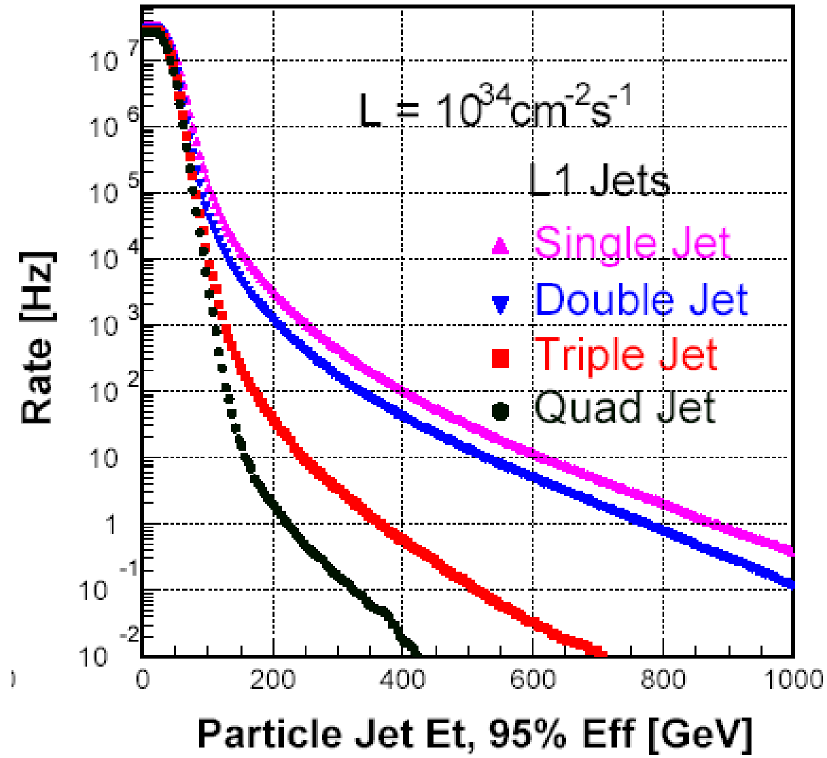
High Luminosity

Total Rate: 100 kHz
Factor 3 safety,
allocate 33.5 kHz

Trigger	Threshold (e=90-95%) (GeV)	Indiv. Rate (kHz)	Cumul rate (kHz)
1e/g, 2e/ g	34, 19	9.4	9.4
1m, 2m	20, 5	7.9	17.3
1t, 2t	101, 67	8.9	25.0
1-jet	250	1.0	25.6
3-jets, 4-jets	110, 95	2.0	26.7
Jet & Miss-ET	113 & 70	4.5	30.4
e & jet	25 & 52	1.3	31.7
m & jet	15 & 40	0.8	32.5
Min-bias		1.0	33.5

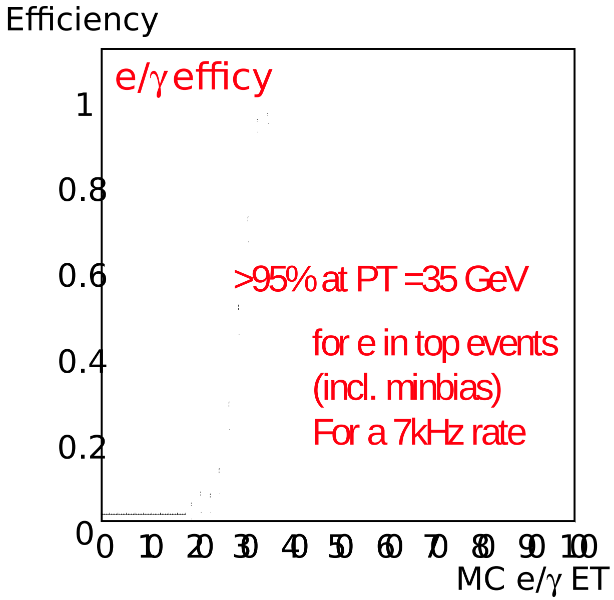
Calorimeter trigger: rates

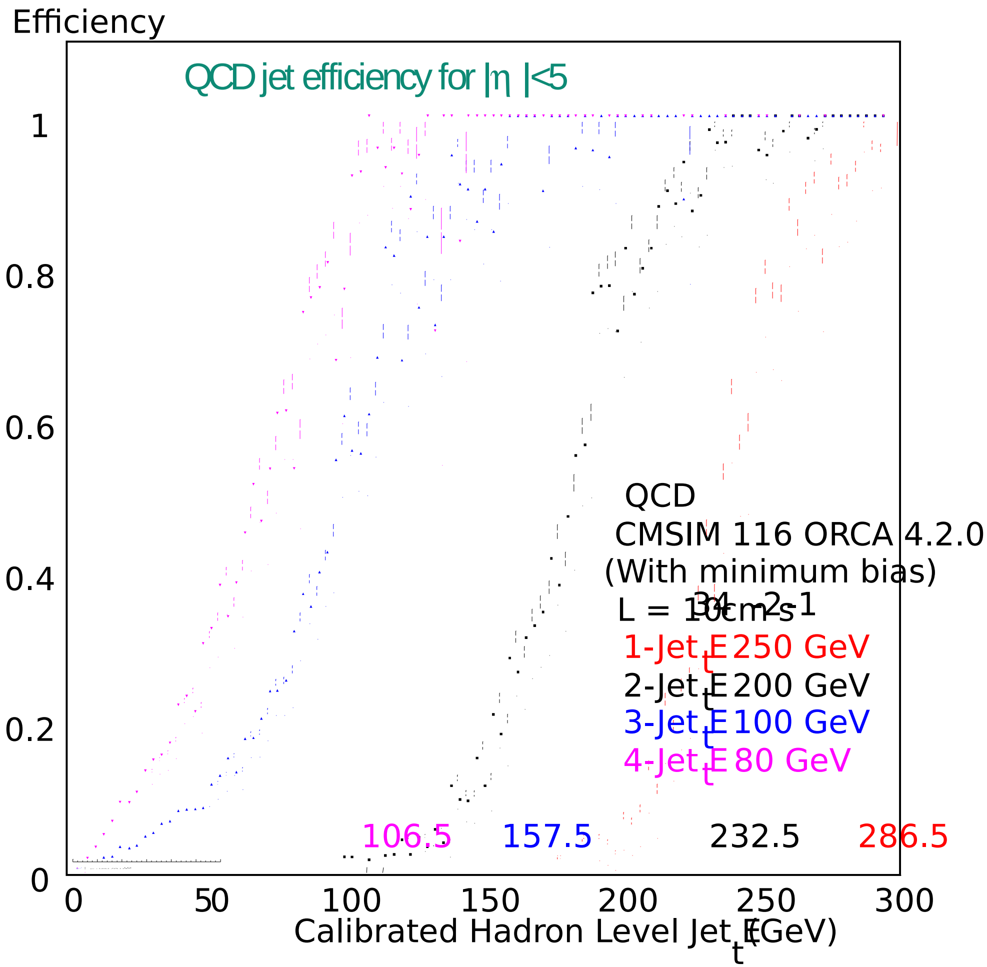


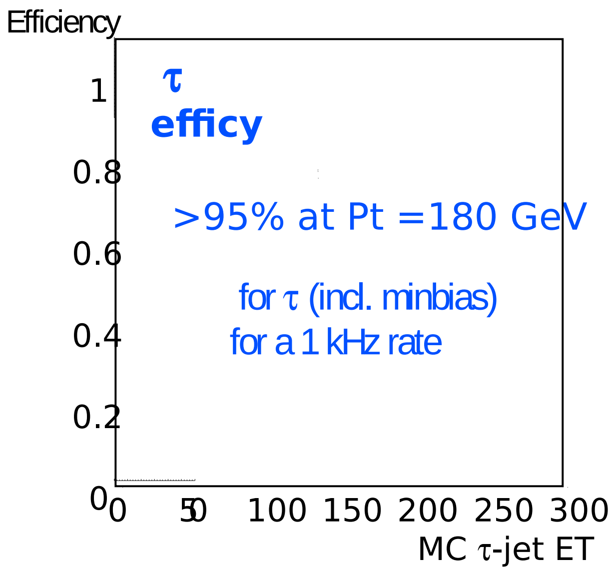


- Simulation

Calorimeter trigger: rates (Simulation)







>95% at PT =286, 232, 157, 106 GeV for individual 1,2,3,4 jet triggers (incl. minbias)

(~0.5 kHz rate each totaling ~2 kHz)

Potentially interesting event categories

- **Standard Model Higgs**
  - If Higgs is light (< 160GeV) : H -> $\gamma\gamma$ H -> ZZ* -> 4l
  - Trigger on electromagnetic clusters, lepton-pairs
  - If Higgs is heavier other channels will be used to detect it
  - H -> ZZ -> ll$\nu\nu$
  - H -> WW -> lνjj
  - H -> ZZ -> lljj
  - Need to trigger on lepton pairs, jets and missing energies

- **Supersymmetry**
  - Neutralinos and Gravitinos generate events with missing Etmiss
  - Squarks decay into multiple jets
  - Higgs might decay into 2 taus (which decay into narrow jets)

Trigger at LHC startup: L=1033cm-2s-1

- **LHC startup**
  - Factor 10 less pile up O(2) interactions per bunch crossing
  - Much less particles in detector
  - Possible to run with lower trigger thresholds

- **B-physics**
  - Trigger on leptons
  - In particular: muons (trigger thresholds can be lower than for electrons)

- **t-quark physics**
  - Trigger on pairs of leptons.

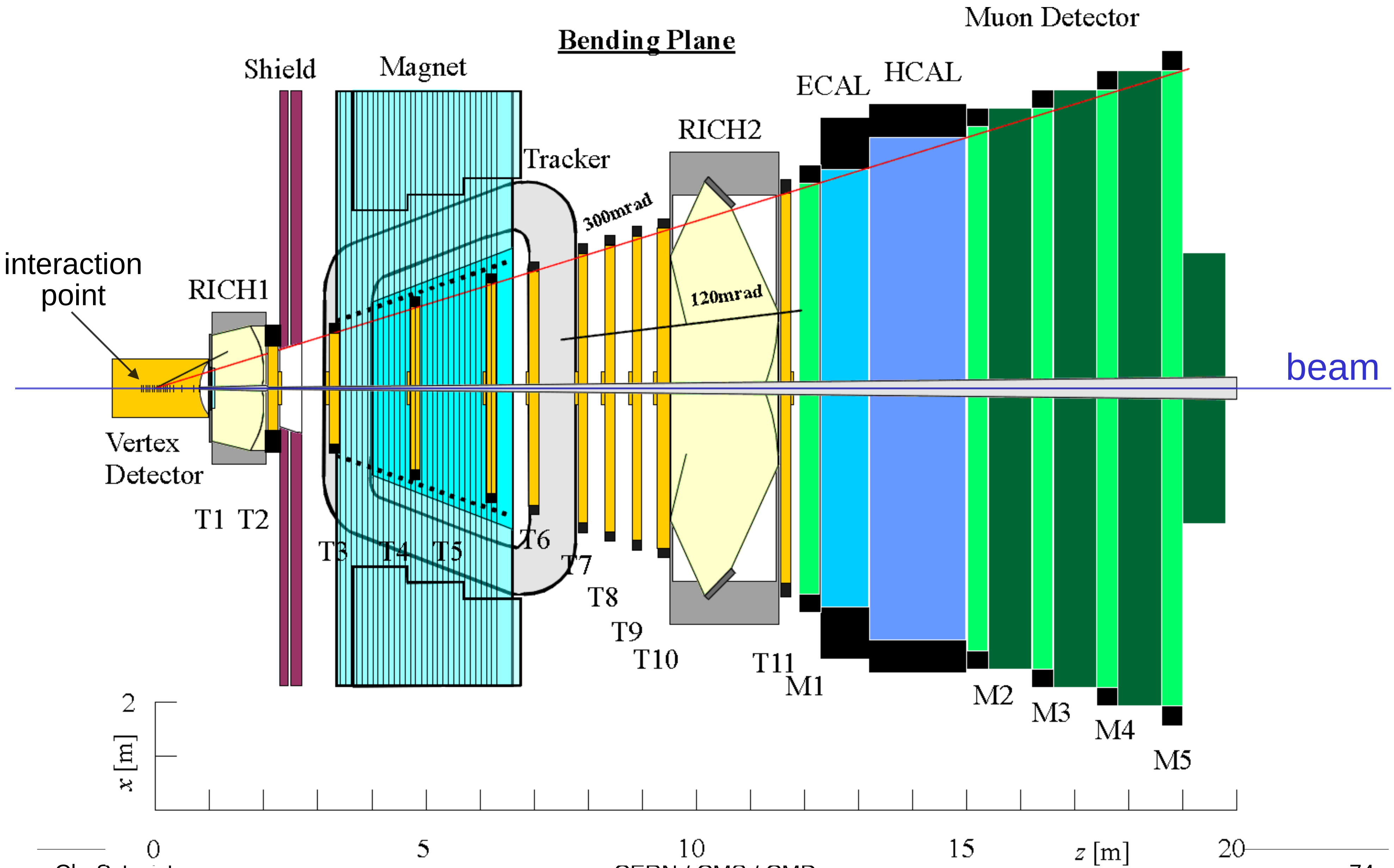
LHCb

- **Operate at L = 2 x 1032 cm-2s-1: 10 MHz event rate**

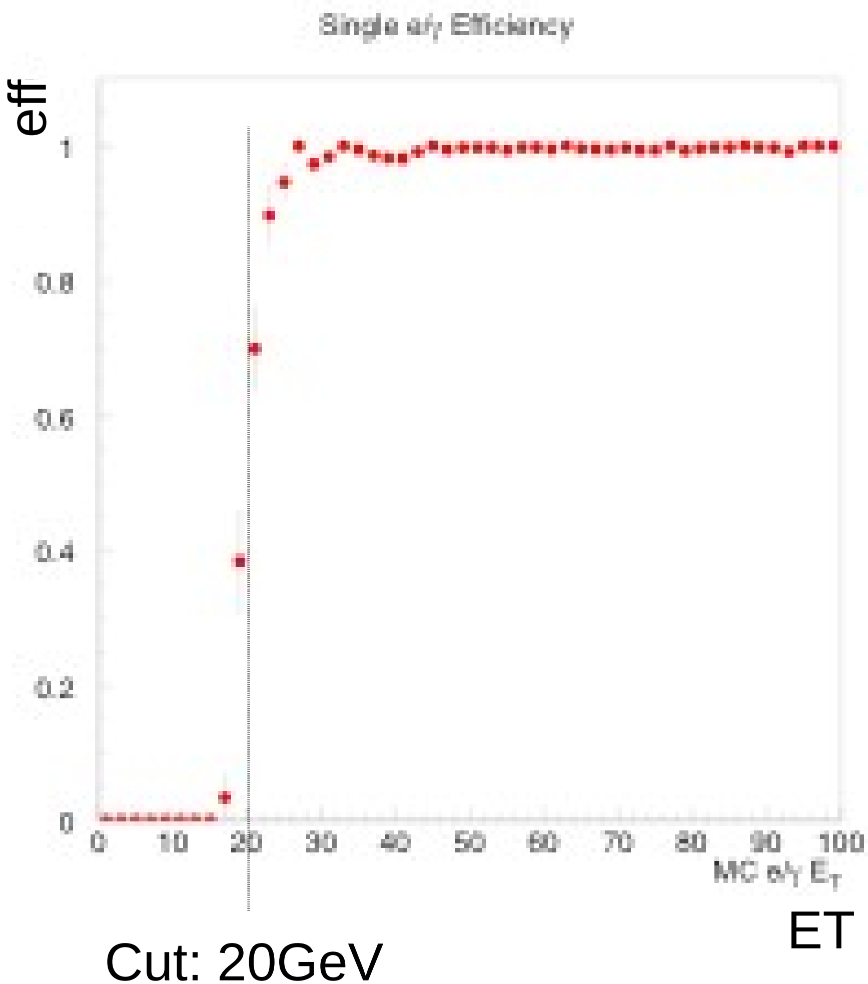
- **Lvl0: 2-4 us latency, 1MHz output**
  - Pile-up veto, calorimeter, muon

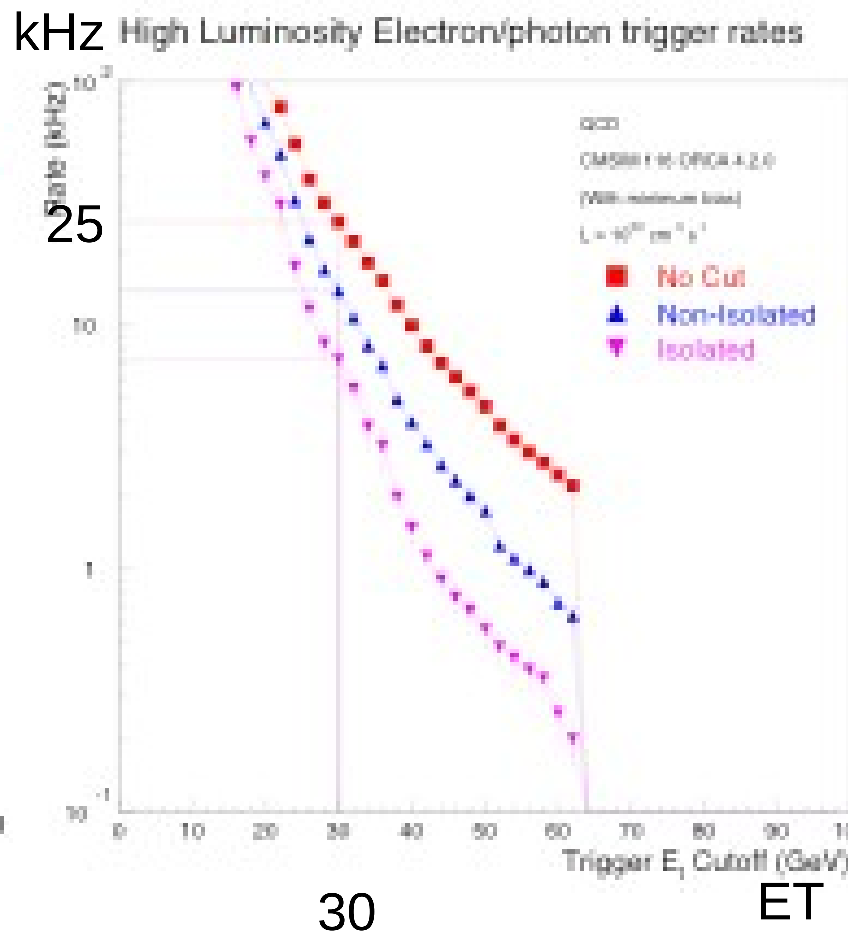
- **Pile up veto**
  - Can only tolerate one interaction per bunch crossing since otherwise always a displaced vertex would be found by trigger

LHCb : study of B-decays (CP̸)



CMS isolated e/γ performance





The 1st level trigger at LHC experiments

Requirement:

Do not introduce (a lot of) dead-time

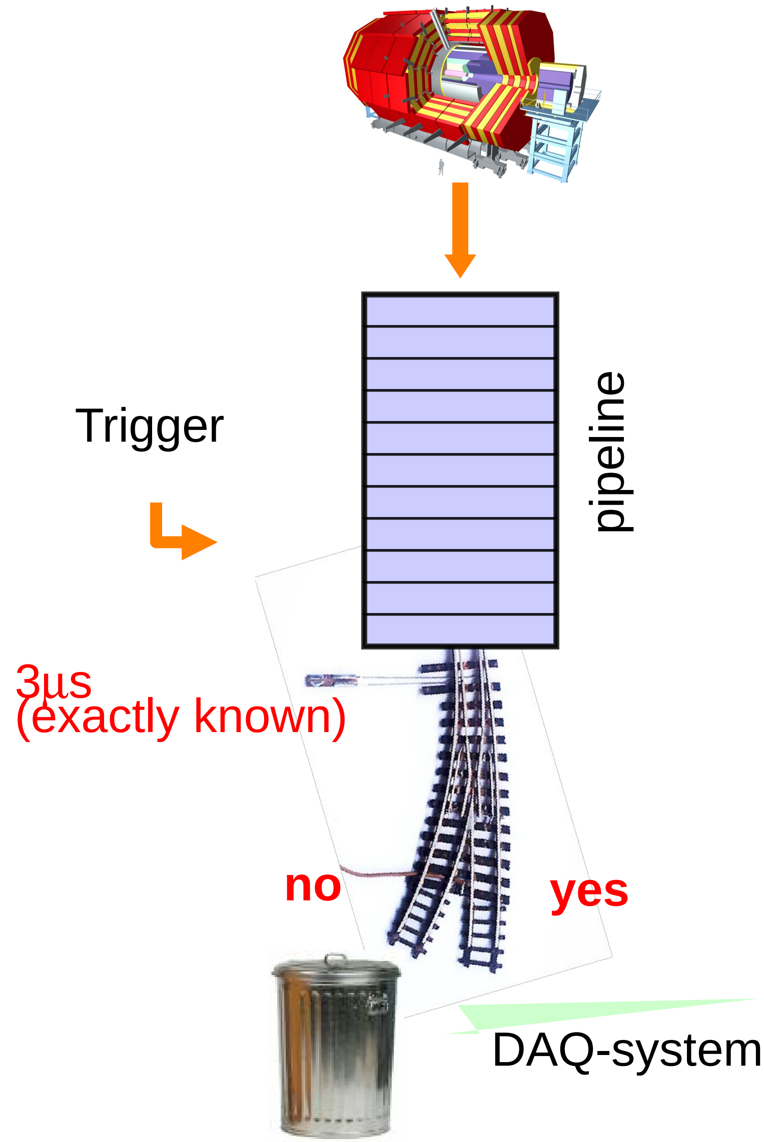
- O(1%) is tolerated
- Introduced by trigger rules :
  not more than n triggers in m BX
- Needed by FE electronics

Need to implement pipelines

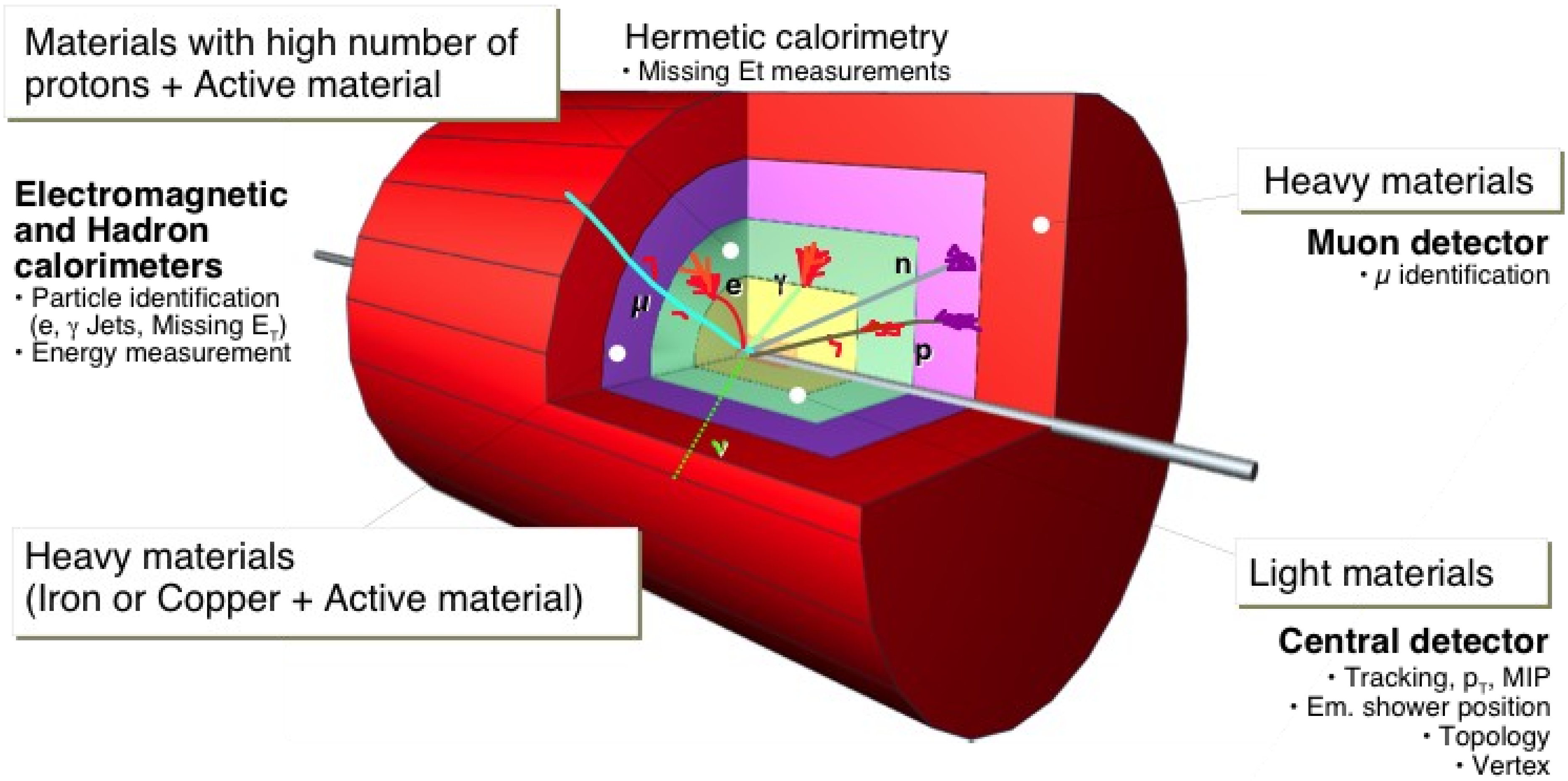
- Need to store data of all BX for latency of 1st level trigger
- Typical : 107 channels / detector
  some GB pipeline memory
  - and derandomizer buffers
- Also the trigger itself is “pipelined”

Trigger must have low latency (2-3 µs)

- Otherwise pipelines would have to be very long



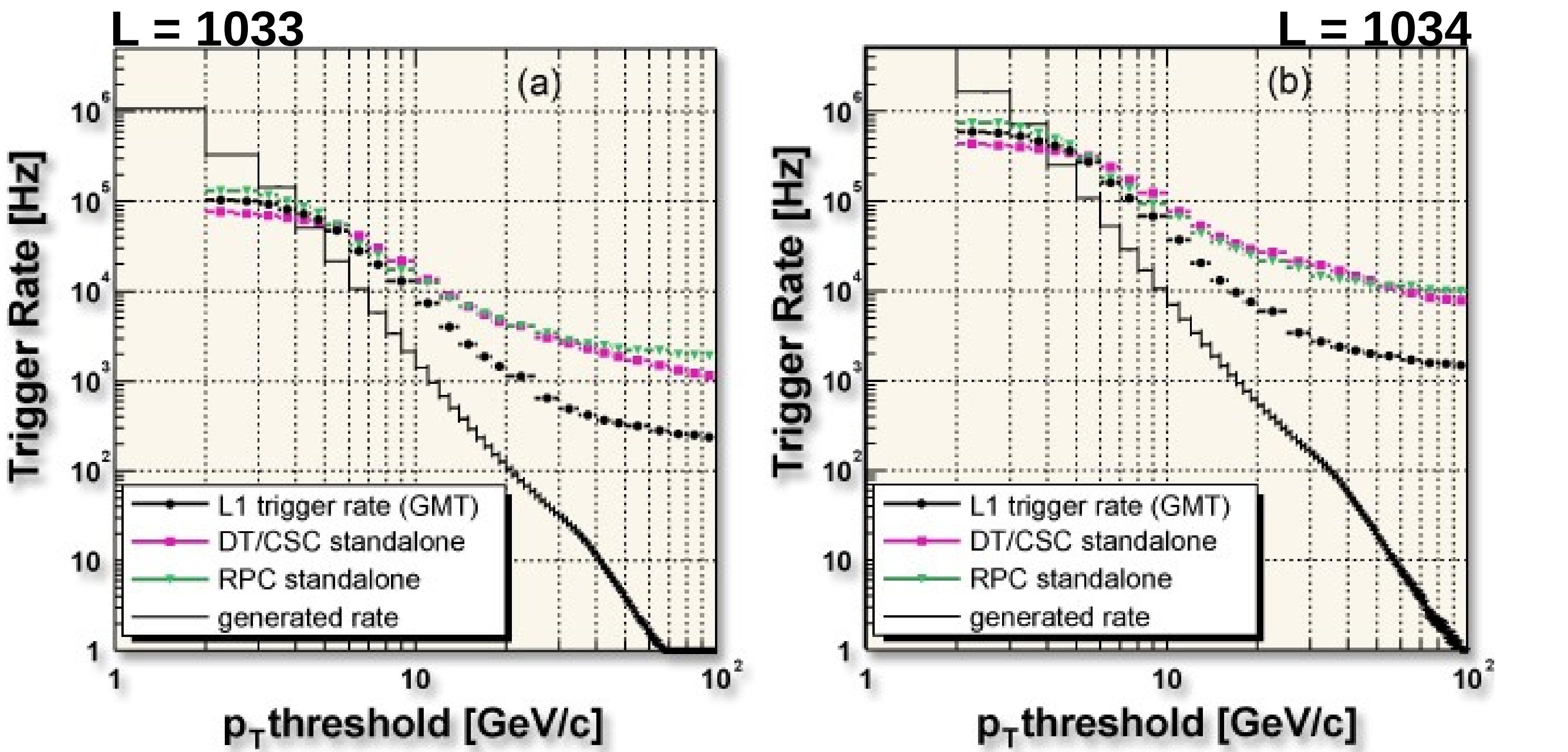
LHC Detector: main principle



Each layer identifies and enables the measurement of the momentum or energy of the particles produced in a collision

Redundancy in the CMS Muon trigger

Generated Muons versus trigger rate (simulation)



pt > 20GeV:

≈ 100 Hz generated,

≈ 1 kHz trigger rate

pt > 20GeV:

≈ 600 Hz generated,

≈ 8 kHz trigger rate

Triggering at LHC : what info can be used

- **Measurements with Calorimeters and Muon chamber system**

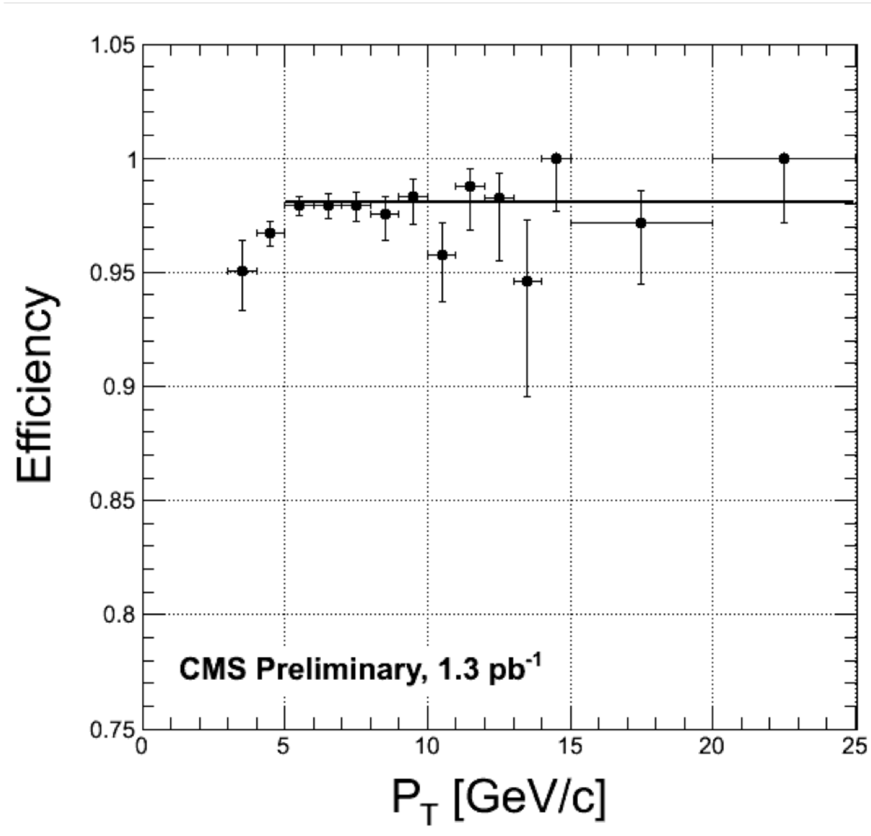
- **Transverse Momentum of muons**
  - Measurement of muon p_t in magnetic field
  - p_t is the interesting quantity:
    - Total p_t is 0 before parton collision (pt conservation)
    - High p_t is indication of hard scattering process (i.e. decay of heavy particle)
    - Detectors can measure precisely p_t
    -

- **Energy**
  - Electromagnetic energy for electrons and photons
  - Hadronic energy for jet measurements, jet counting, tau identification
  - Like for momentum measurement: E_t is the interesting quantity
  - Missing E_t can be determined (important for new physics)

Muon Track Finding Efficiency (CMS DT)

•**Technique tag & probe**

- J/Ψ -> μμ,
- one μ satisfied trigger, the other used to measure efficiency
- Inefficiency understood hardware problem



Trigger implementation (II)

- **ASIC (Application Specific Integrated Circuit)**
  - Can be produced radiation tolerant (for “on detector” electronics)
  - Can contain “mixed” design: analog and digital electronics
  - Various design methods: from transistor level to high level libraries
  - In some cases more economic (large numbers, or specific functionality)
  - Disadvantages:
  - Higher development “risk” (a development cycle is expensive)
  - Long development cycles than FPGAs
    - No bugs tolerable -> extensive simulation necessary

- **Example :**
  - ASIC to determine ET and to identify the Bunch Crossing (BX) from the ATLAS calorimeter signals
  - Coincidence matrix in Muon Trigger of ATLAS

Trigger implementation (III)

- **Key characteristics of Trigger Electronic boards**

  - Large cards because of large number of IO channels

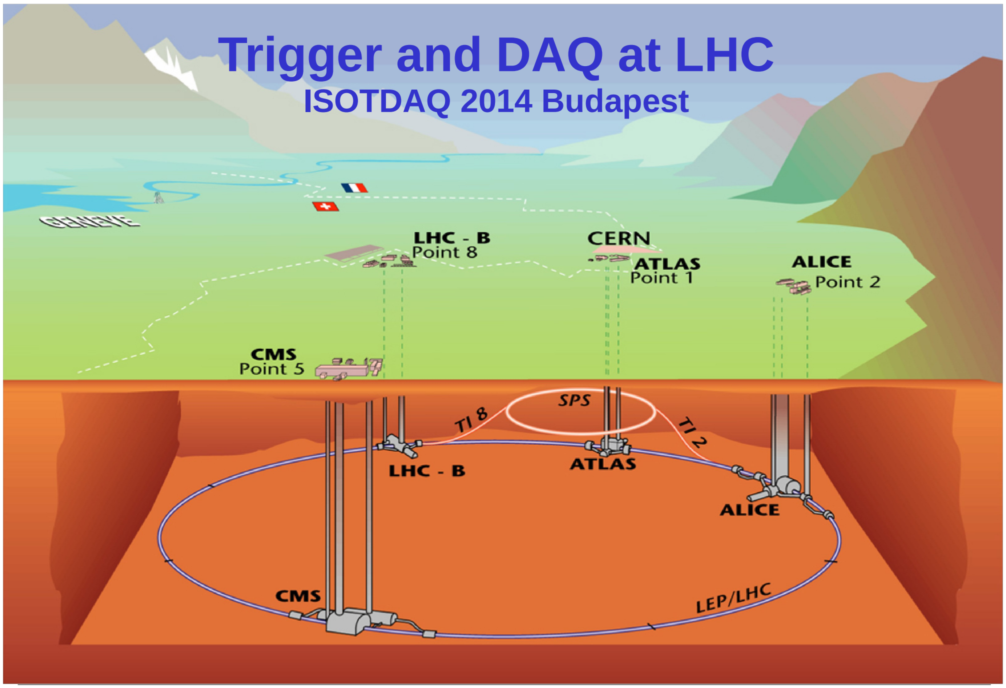
  - Many identical channels processing data in parallel
  - This keeps latency low

  - Pipelined architecture
  - New data arrives every 25ns

  - Custom high speed links
  - Backplane parallel busses for in-crate connections
  - LVDS links for short (O(10m)) inter-crate connections
    (LVDS: Low Voltage Differential Signaling)

Trigger and DAQ at LHC

ISOTDAQ 2014 Budapest



C.Schwick

Contents

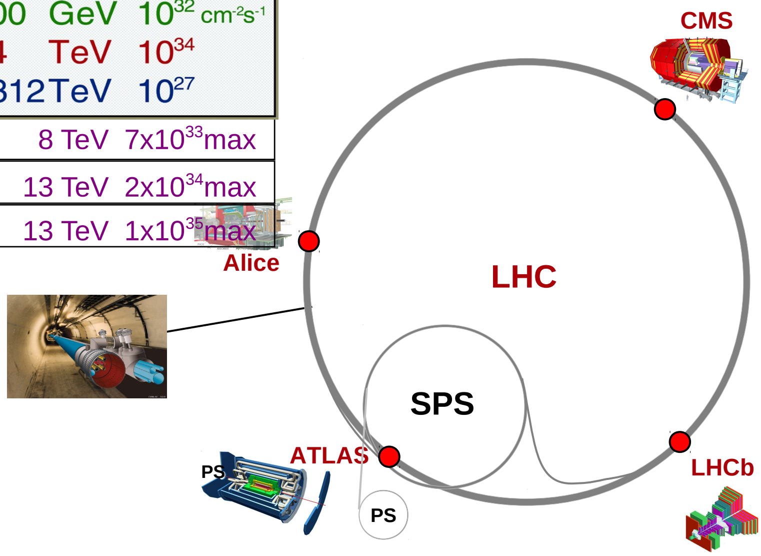
- **Acknowledgement**
  - Thanks to many of my colleagues in ALICE, ATLAS, CMS, LHCB for the help they gave me while preparing these lectures; and in particular to Sergio Cittolin who provided me with many slides (probably those you will like most are from him!)

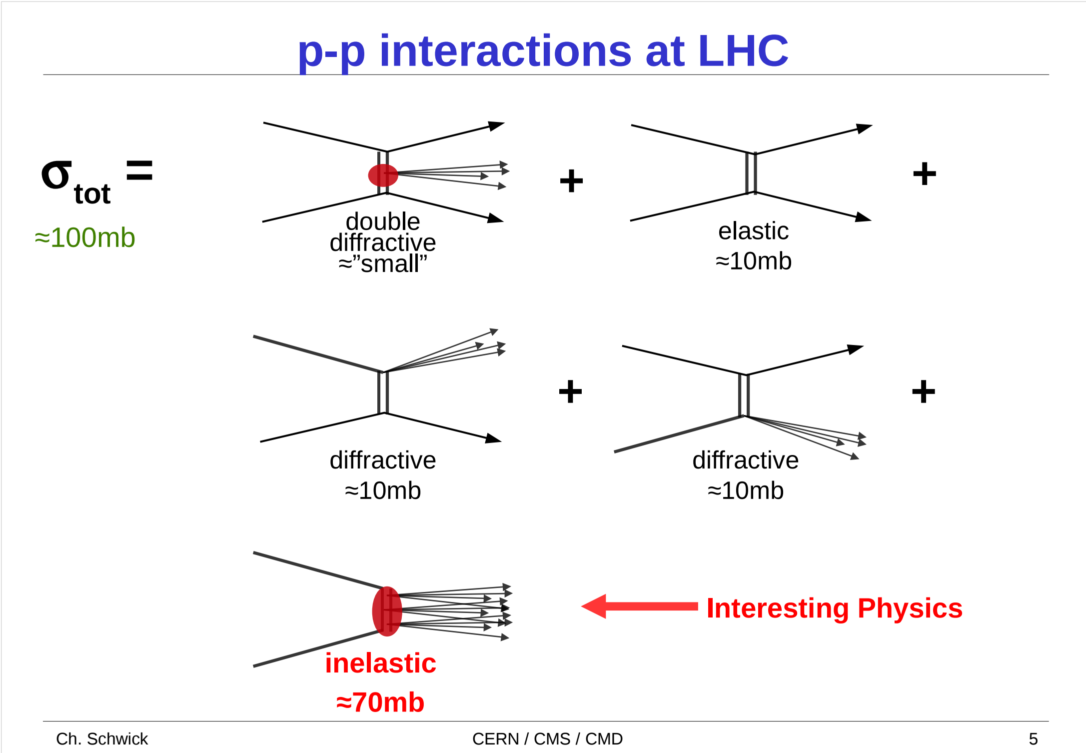
Introduction: LHC and the Experiments

LHC: a “discovery” machine

	Beams	Energy		Luminosity
LEP	e^+e^-	200	GeV	10^{32} $cm^{-2}s^{-1}$
LHC	p p	14	TeV	10^{34}
	P_b P_b	1312	TeV	10^{27}

LHC 2012	pp	8 TeV	$7x10^{33}$max
LHC 2015	pp	13 TeV	$2x10^{34}$max
LHC 2023	pp	13 TeV	$1x10^{35}$max

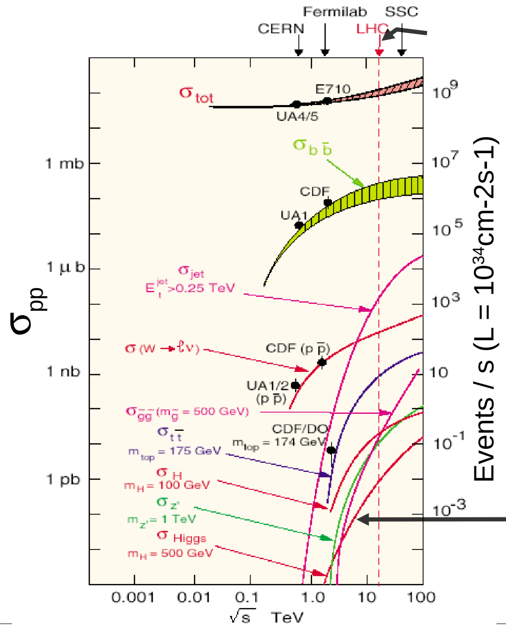




In order to know what challenges to expect when constructing Trigger DAQ it is Instructive to look at interactions

Pomeron Exchange
Pomeron: colorless object (example g-g, photon)
Diffractive and elastic processes: low Q2 : limited physics interest (no "new" physics expected since new particles are expected to be very heavy and therefore need high Q2 interactions),
difficult to analyse since many overlapping events

Interesting Physics at LHC



$\sigma_{tot} \approx 100$ mb

1 : 100 000 000 000

$\sigma_{H(500GeV)} \approx 1$ pb
a needle in the haystack

Focus on right hand scale: Rates at full luminosity

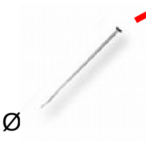
For an experimentalist a very useful plot since many experimental challenges can be read off:
- 100mB correspond to10^9 interactions per second
- sigma jet= 1000/second
- sigma higgs = 1 per 100 seconds

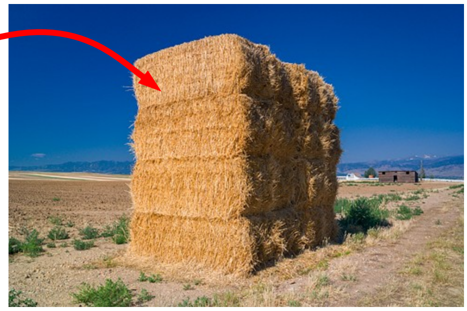
Ratio is like 1ms in 3 years

Is the Higgs a needle in the hay stack?

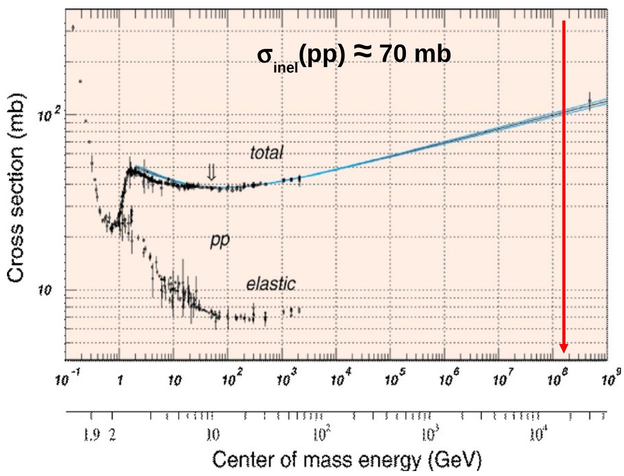
- **Hay stem:**
  - 500mm length, 2mm Ø
    → 3000 mm^3
- **Needle**
  - 50 mm length, 0.3mm Ø
    → 50 mm^3
  - 50 needles are one hay stem
- **Putting it all together**
  - Assume hay packing density of 10
    (...may be optimistic...)

    Haystack of 50 m^3





LHC: experimental environment



$L = 10^{34} cm^{-2}s^{-1}$

$\sigma_{inel}(pp) \approx 70mb$

event rate = 7 x 10^8 Hz

Δt = 25ns

events / 25ns = 17.5

Not all bunches full (2835/3564)

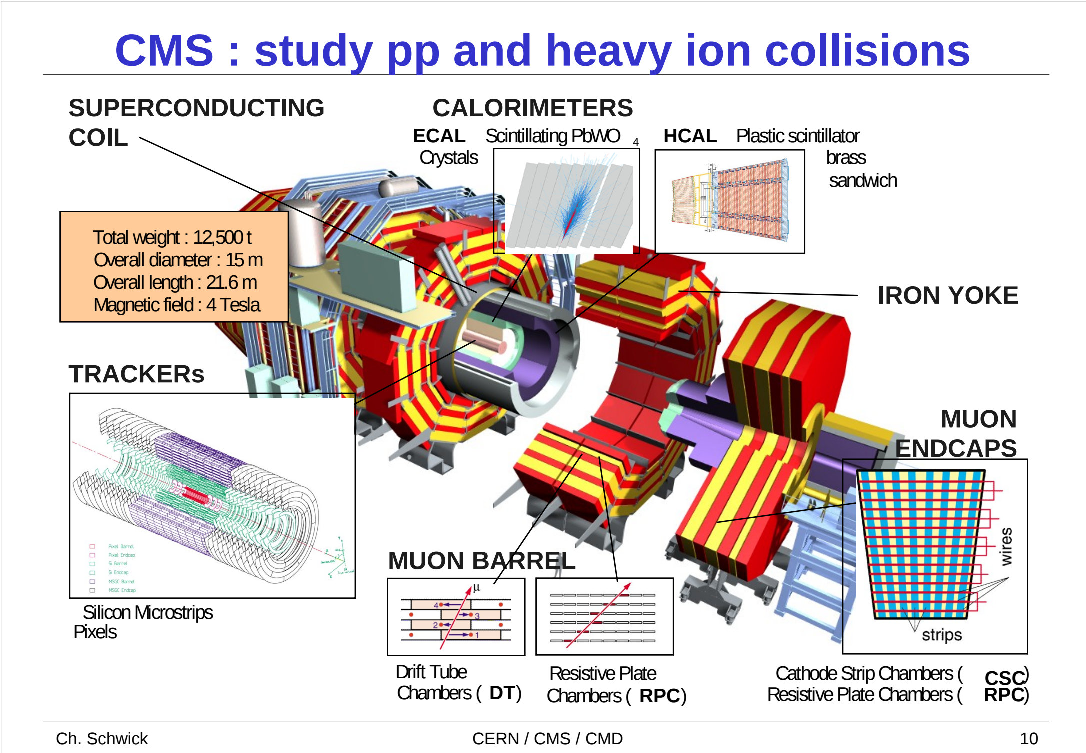
events/crossing = 23

2012 LHC ran at 50ns
pile up was twice as high as for 25 ns (at constant Lumi)

Explain number events per crossing / luminosity per bunch

Inel = tot - el - diffractive = 100 - 10 - 2*10

The 4 largest LHC experiments

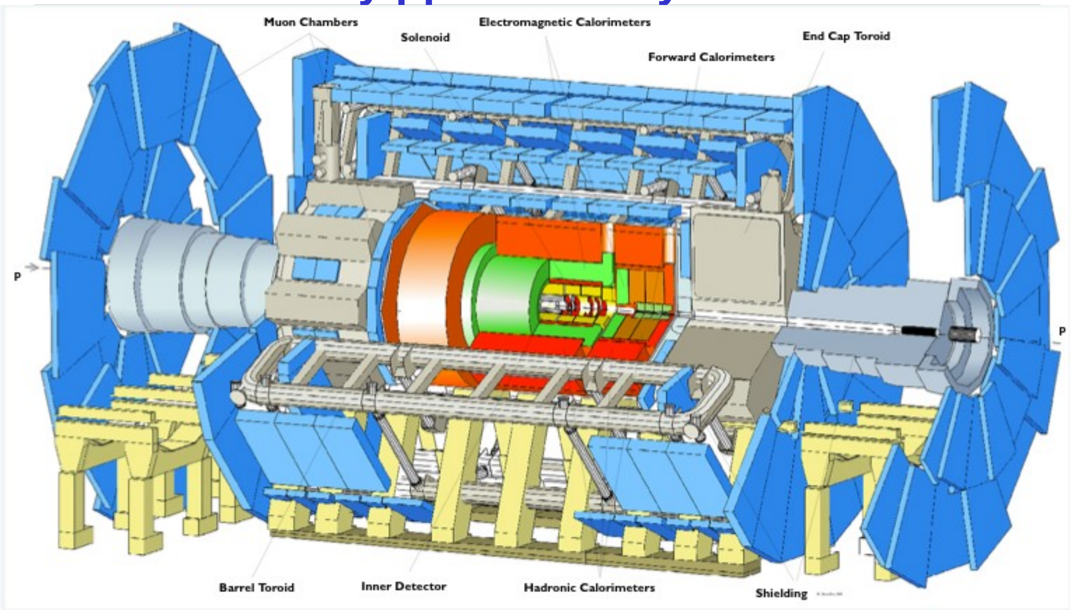


Pixel detector: 26*10^6 pixels on half a sqm
Si tracker 250sqm (25 m swimming pool),

Lead tungsten crystals : seem glass but 98% metal
Surface of DT chambers: soccer field 1300m^2
HCAL calorimeter: example of recycling: russian bras bullet casing

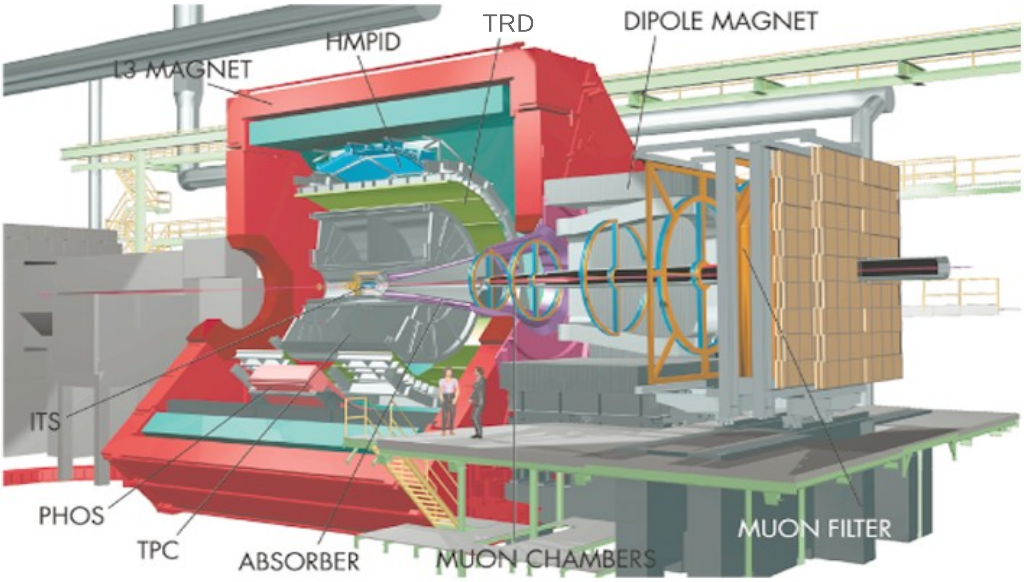
Metal in return yoke is roughly equivalent to amount in the Eiffel tower of Paris
12500 tonnes: In water it sinks

Atlas : study pp and heavy ion collisions



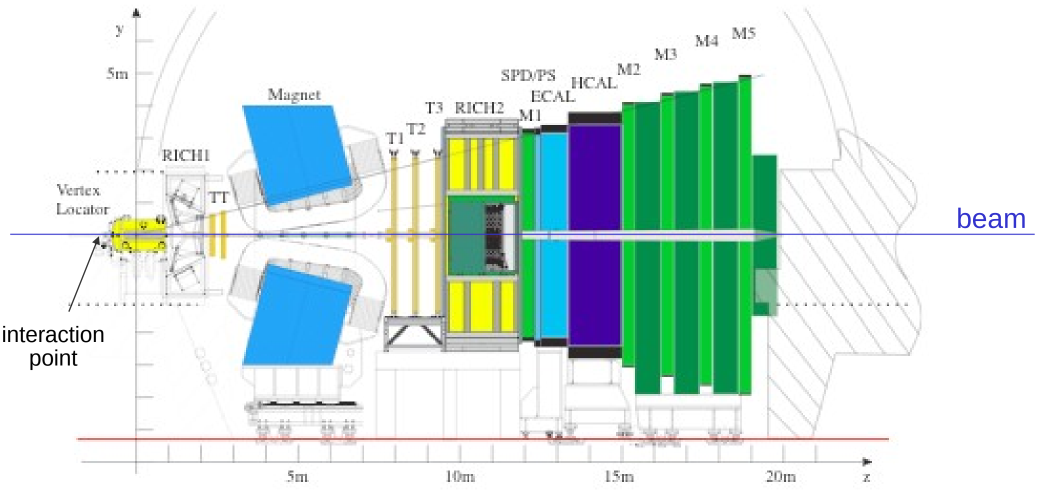
If you throw atlas into water it swims
Half the weight of CMS (6000t): 8 times the volume of CMS: It swims
Particular: toroid air coil: good muon momentum resolution

ALICE : study heavy ion collisions



Central part in re-cycled L3 Magnet
Asymmetric:Muon arm for muon spectroscopy: J/Psi decays in muons-> J/Psi indicator for ccbar production
Number of coupled ccbars indicate in how far the quarks are still bound or are moving free in a plasma.
PHOS to detect high pt “hot” photons emerging from quark gluon plasma
HMPID : cerenkov detector for high pt particle id
TOF particle ID (impl RPC) particle id In medium momentum region (low : TPC)
TRD: separation electrons from pions (PPC) (via energy deposited in TRD)
Used in trigger L1 (6.5us): several layers of TRD make tracklets, Computes invariant mass of pairs (J/psi)
Direction and vertex constraint: pt
TRD for electron pairs (strange enhancement)
Trigger: ZDC FMD multiplicity, measure of “centrality”
Inner Tracking system contains silicon Drift Detector
TPC for tracking

LHCb : study of B-decays (~~CP~~)

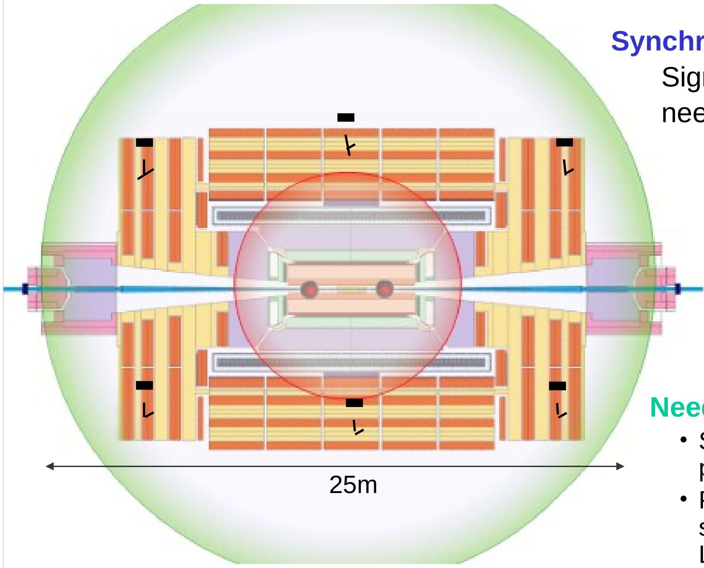


Ch. Schwick CERN / CMS / CMD 13

Vertex Locator: VELO: precise vertex detector
RHICHes particle ID (pion muon e- discrimination)
Tracking chambers before and after a magnet -> momentum measurements

Timing and Synchronization

Issue: synchronization



Synchronization:

Signals/Data from the same BX need to be processed together

But:

Particle TOF >> 25ns

(25 ns ≈ 7.5m)

Cable delay >> 25ns

($v_{signal} \approx 1/3\ c$)

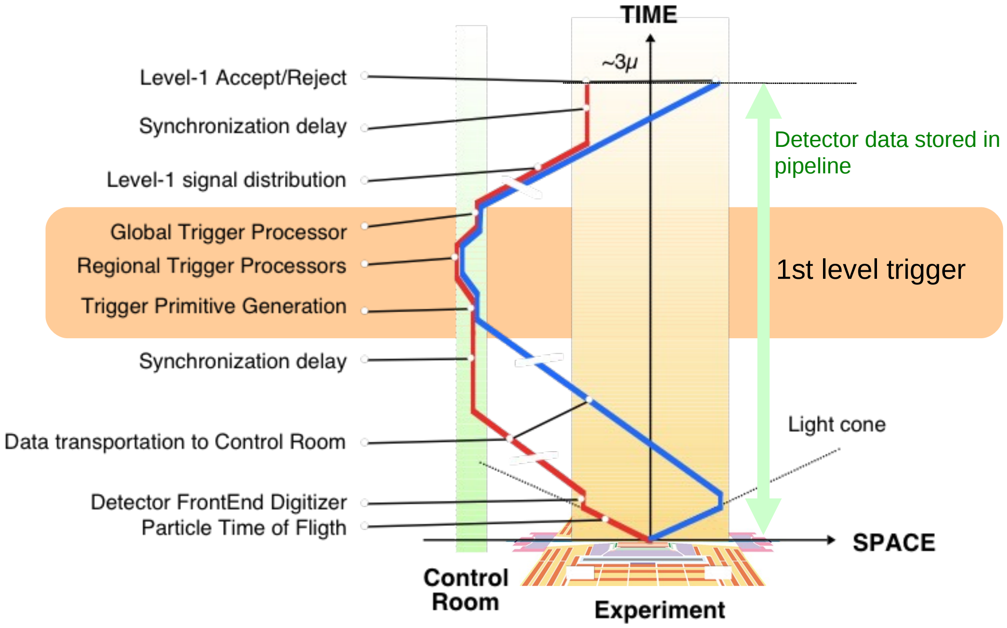
Electronic delays

Need to:

- Synchronize signals with programmable delays.
- Provide tools to perform synchronization (TDCs, pulsers, LHC beam with few buckets filled…)

A particular issue at LHC is related to the size of the experiments and the short BX interval
Cable : 5ns/m
7.5 m in 25 ns for speed of light

Signal path during trigger



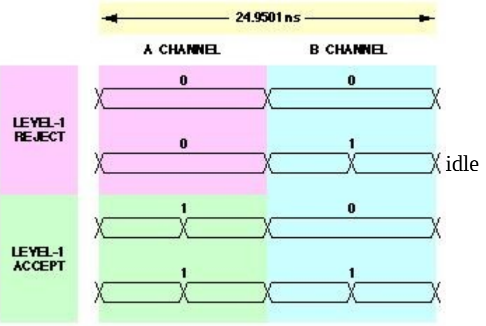
This picture has approximately correct scales
Approximately 500ns to process data !! The rest propagation delay

Distribution of Trigger signals

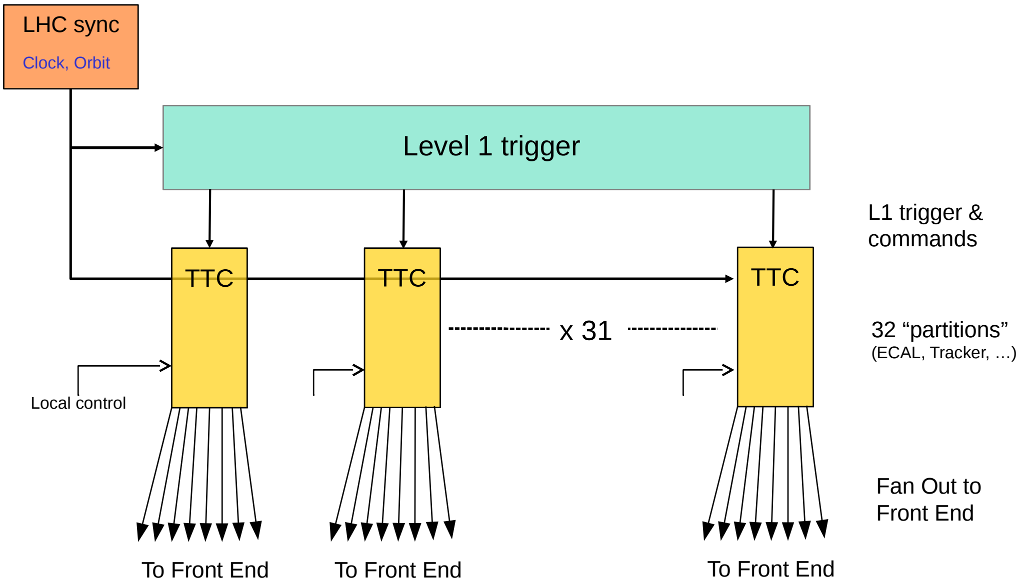
- **The L1 trigger decision needs to be distributed to the front end electronics**
  - Triggers the readout of pipeline
  - Needs to allow to determine the Bunch Crossing of the interaction
    - Timing needs to be precise (low jitter, much below 1ns)
    - Signal needs to be synchronized to LHC clock
- **In addition some commands need to be distributed:**
  - always synchronous to LHC clock; e.g.
    - To do calibration in LHC gap (empty LHC buckets)
    - Broadcast reset and resynchronization commands
- **Used by all experiments: TTC (Trigger Timing and Control)**

TTC encoding: 2 Channels

- **Channel A:**
  - One bit every 25ns
  - constant latency required
    - Used to read out pipelines
  - For distribution of Lvl1-accept
- **Channel B:**
  - One Bit every 25 ns
  - Synchronous commands
    - Arrive in fixed relation to LHC Orbit signal
  - Asynchronous commands
    - No guaranteed latency or time relation
  - "Short" broadcast-commands (Bunch Counter Reset, LHC-Orbit)
  - "Long" commands with addressing scheme
    - Serves special sub-system purposes



Trigger, Timing, Control at LHC



First Level Trigger

Three very different real world examples

	LEP	DaΦne	LHC
physics	e+ / e-	e+ / e-	p / p
Event size	O(100 kB)	O(5 kB)	2013: (1MB for CMS & ATLAS)
1/fBX	22µs (later 11µs)	2.7 ns	25 ns
Lvl1 Trig.	Decision between 2 bunch crossings	Continuously running; trigger readout on activity	2013: Synchronous to 40Mhz base clock; decision within 3us latency; pipeline
trigger rate	O(10Hz)	50kHz	2013: 100kHz (1MHz LHCb) 2023: 1MHz (40MHz LHCb)

Transition

You have already seen many nice metaphors for the Trigger during this school:

Here another one:

Immagine you were responsible

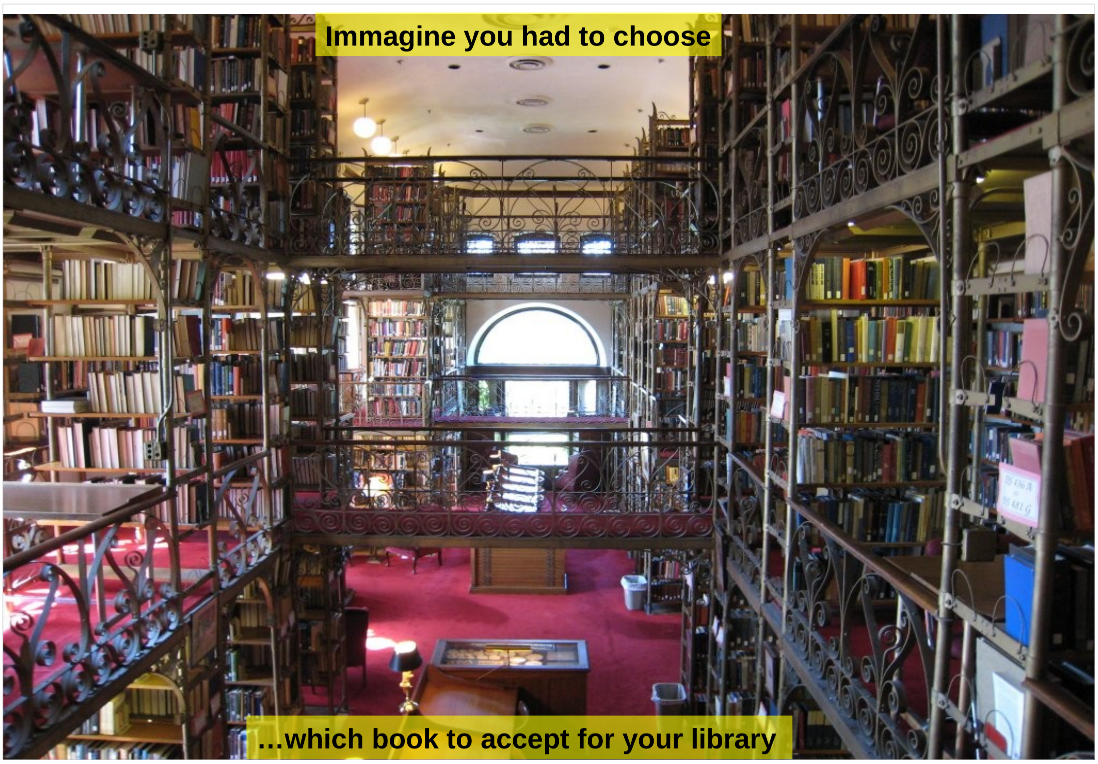
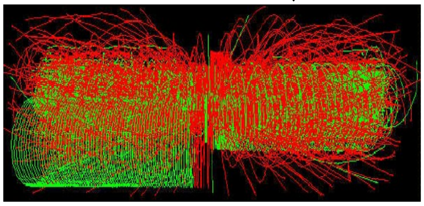


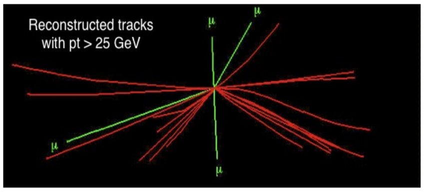
Immagine you had to choose
...which book to accept for your library

TABLE OF CONTENTS.

“Typical event”

H -> Z0Z0 -> 4μ





Prepare an “event – TOC”

- Data must be available fast (I.e. shortly after the interaction)
  - Some sub-detectors are build for triggering purposes
- Prepare data with low resolution and low latency in sub-detectors

Therefore for ATLAS and CMS:

- Use only calorimeter and muon data

Track reconstruction for trigger would have been too complex with available technology.

But there are upgrade plans…

Before we go into some more detail on how to build a trigger let us deal with
Another particularly important problem in LHC experiments:

Signal synchronizations:

Detectors are large, signals are fast

First Level Trigger of ATLAS and CMS

Triggering at LHC

- **The trigger dilemma:**
  - Achieve **highest efficiency for interesting events**
  - Keep **trigger rate as low as possible (high purity)**
    - Most of the interactions (called minimum bias events) are not interesting
    - DAQ system has limited capacity
- **Need to study event properties**
  - Find differences between minimum bias events and interesting events
  - Use these to do the trigger selection

Triggering wrongly is dangerous:

Once you throw away data in the 1st level trigger, it is lost for ever

- Offline you can only study events which the trigger has accepted!
- Important: must determine the trigger efficiency (which enters in the formulas for the physics quantities you want to measure)
- A small rate of events is taken “at random” in order to verify the trigger algorithms (“what would the trigger have done with this event”)
- Redundancy in the trigger system is used to measure inefficiencies

Unfortunately triggering is a business of conflicting interests.

If you have solved the synchronization problems what remains is the classical trigger dilemma

Boundary conditions for level 1

- **Max trigger rate**
  - DAQ systems of CMS/ATLAS designed for approx. **100 kHz**
  - Assumes average event size of **1-1.5 MB**.

  - Trigger rate estimation
  - Difficult task since depends on lots of unknown quantities:
    - Physics processes are not known at this energy (extrapolation from lower energy experiments)
    - Beam quality
    - Noise conditions

- **Trigger was designed to fire with ≈ 35 kHz**
  - Security margin 3 for unforeseen situations like noise, dirty beam conditions, unexpected detector behavior

- **Trigger design needs to be flexible**
  - need many handles to adjust the rates.

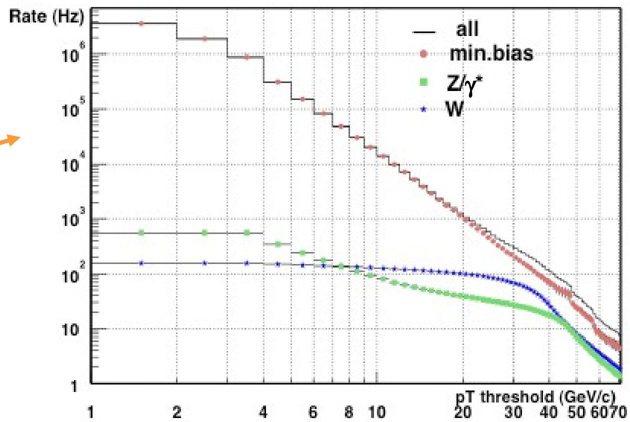
Triggering at LHC : example Muons

- **Minimum bias events in pp:**
  - Minimum bias: decays of quarks e.g. pions (SM)
- **"Interesting" events**
  - Often W/Z as decay products

L = 10^{34}

Example: single muons min. bias vs W/Z decays

Threshold ≈ 10 GeV
Rate ≈ 20 kHz



Plot made WITHOUT detector simulation

High threshold fortunately possible since interesting spectrum falls of pretty late
Large uncertaint: extrapolation from lower energy experiments

Interesting rate @ 1GeV: 170+530= 700Hz
Min Bias rate @ 1GeV: 3.8 Mhz
S/N : 0.0002

Interesting rate @ 10GeV: 90+110=200Hz
Min Bias rate @ 10GeV: 20 kHz
S/N : 0.01 : Improved by factor 50 while rate went down by factor 200

@20GeV: 100+39=130
Min Bias: 1kHz
S/N 0.13

Cont’ed: triggering on Muons

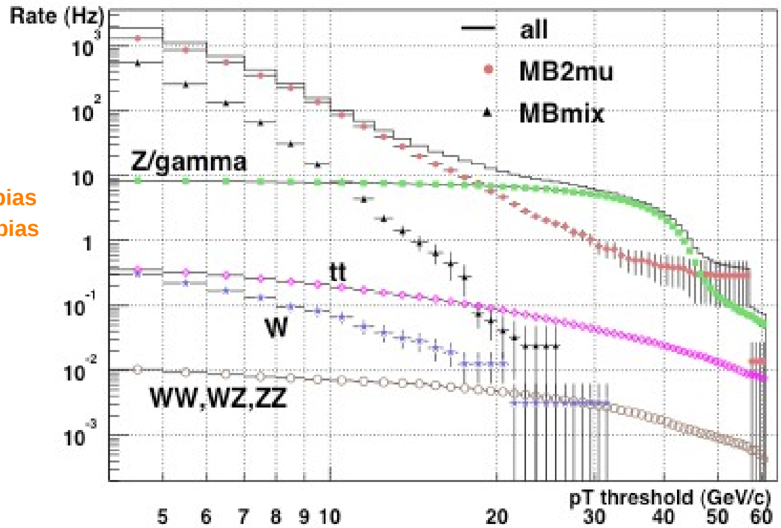
- **Interesting events: contains (almost) always 2 objects to trigger on**

L = 10^{34}

Example muon pairs :

MB2mu : 2μ from min bias
Mbmix : 1μ from min bias

Threshold ≈ 10 GeV
Rate ≈ 100Hz

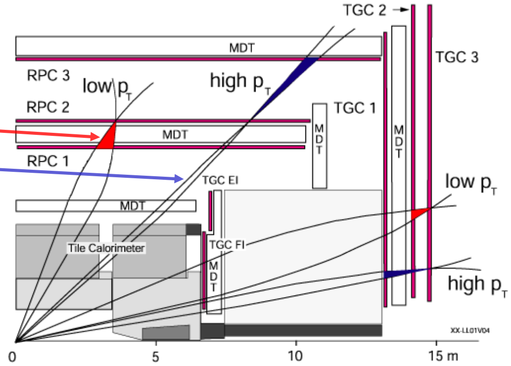


Again: exploit the difference in shape : the interesting curves are flatter than the minimum bias curves => allow to improve signal to noise while reducing the rate

Rate reduction: 2kHz vs 100Hz : 20
S/N 10/20k vs 10/100 : 20

How to trigger on Muons

- **Example ATLAS muon trigger**
  - Three muon detectors:
    - Muon Drift Tubes (MDT) : high precision, too slow for level 1 trigger
    - Resistive Plate Chambers (RPC) : 1st level trigger barrel
    - Thin Gap Chambers (TGC) : 1st level trigger endcap
  - **Measure p_t** by forming coincidences in various layers:
    - Low p_t : 2 layers
    - High p_t: 3 layers
  - "**Coincidence matrix**"
    - Implemented with ASIC (Application Specific Integrated Circuit)

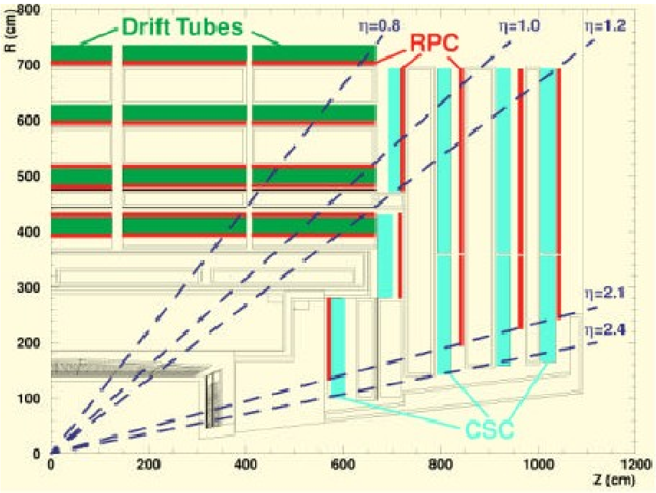


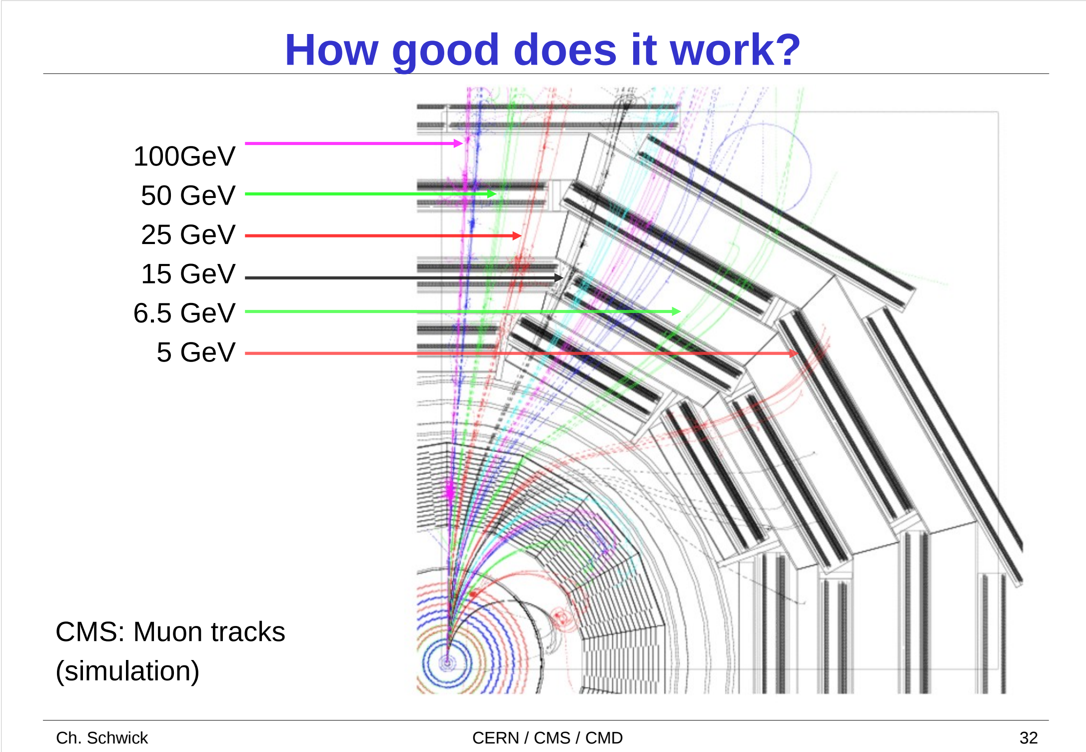
…That was theory: how is it done in the real life…

ATLAS has Toroid magnet, show to explain

How to trigger on Muons

The CMS muon system



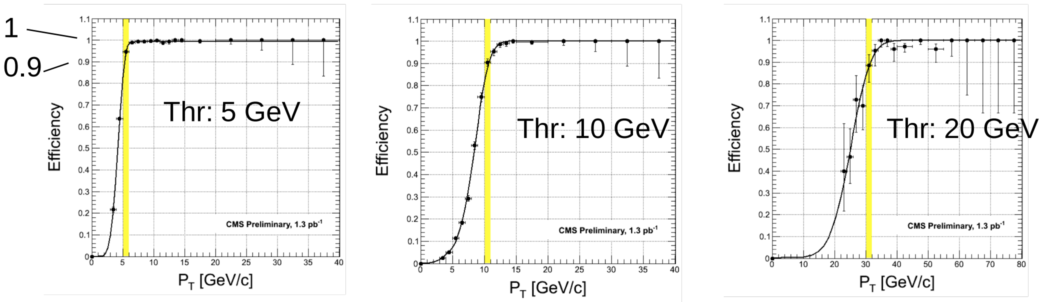


1) Explain the S curve

A lot of material: Iron of return yoke from Magnet, Brass of hadron calorimeter, Electromagnetic calorimeter
Two effects influence the resolution : clear from this picture:
Low momentum: multiple scattering in material
High momentum: detector resoultion (especially in case of trigger)

Performance of CMS muon trigger

- **Efficiency turn-on curves**



- From Data with events: J/ψ → μμ and Z → μμ
- “Real” pt vs. efficiency for imposed trigger threshold
- For an imposed threshold x the efficiency for muons with pt = x GeV is larger 90% (…as foreseen).

Real Pt (determined from data anlysis with tight quality criteria)

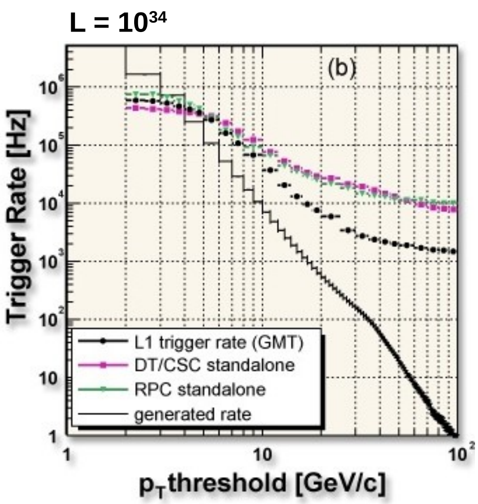
vs

Efficiency for single muon trigger pt at given threshold

Ideal world : Step function

Redundancy in the CMS Muon trigger

Generated Muons versus trigger rate (simulation)



Redundancy allows to impose tight quality cuts (i.e. number of hits required for each muon, …)

this improves purity

p_t > 20GeV:

≈ 600 Hz generated,

≈ 8 kHz trigger rate

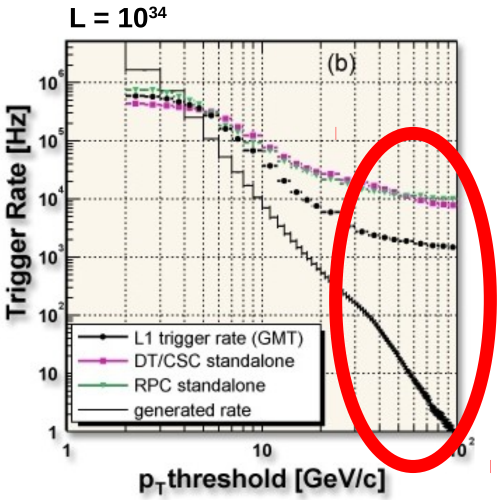
This plot is done WITH detector simulation! The previous not!

You see how redundancy in the trigger system helps

Show why multiple detectors are useful here: redundancy allows to reduce the trigger rate (cutting on quality no of hits, …)

But: Let's have a closer look...

Generated Muons versus trigger rate (simulation)



Trigger rate stays high even when thresholds is increased !!!

Why??? - Low Pt muons are mis-identified (There are a LOT of low pt particles in the forward region)

Problem for Lumi > n x 10^{34}

UPGRADE:

Finer granularity in forward region and additional chambers: less mis-identification

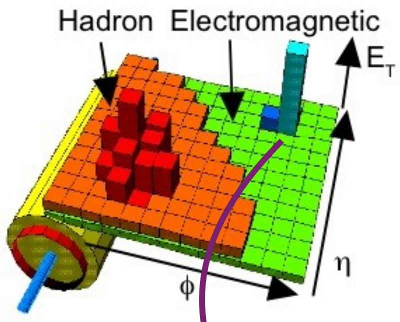
New Trigger Logic (see later)

This plot is done WITH detector simulation! The previous not!

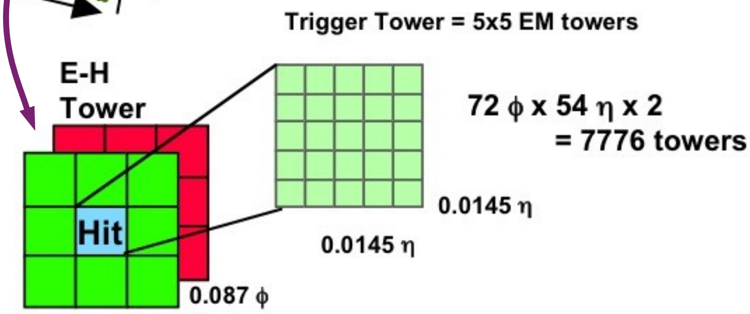
You see how redundancy in the trigger system helps

Show why multiple detectors are useful here: redundancy allows to reduce the trigger rate (cutting on quality no of hits, …)

Calorimeter Trigger: example CMS



Divide Calorimeter into towers
Match towers between ECAL and HCAL



Scope: find e/gamma, tau and jet
==> need em and had energy correlated
==> build matching towers

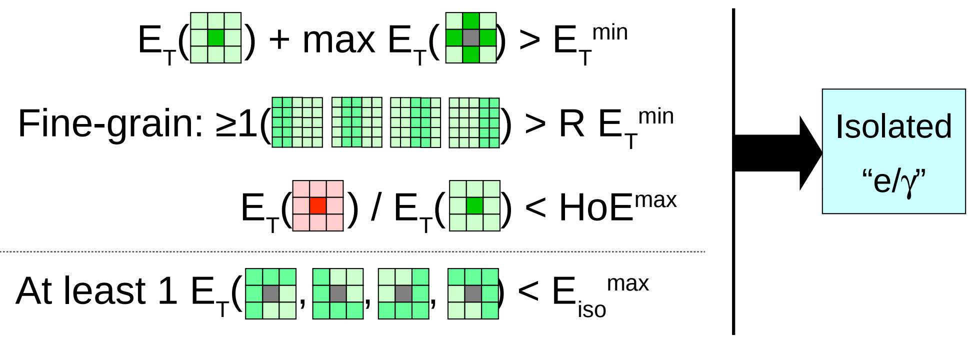
Reduce resolution for trigger

Cannot process data at full resolution in 2-3us

Algorithm to identify e/γ

Characteristics of isolated e/γ:

- energy is locally concentrated (opposed to jets)
- energy is located in ECAL, not in HCAL



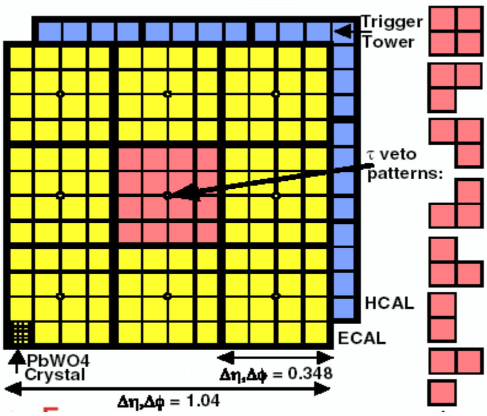
SLIDING window : in practice: all in parallel

1st minimum Et available in center + 1 neighbour
2nd on a finer level: energy concentrated in a stripe
3rd no energy in hcal
4th not a lot of energy in surrounding

How to find these algos: MC

Calorimeter Trigger: jets and Taus

- **Algorithms to trigger on jets and tau:**
  - based on clusters 4x4 towers
  - Sliding window of 3x3 clusters



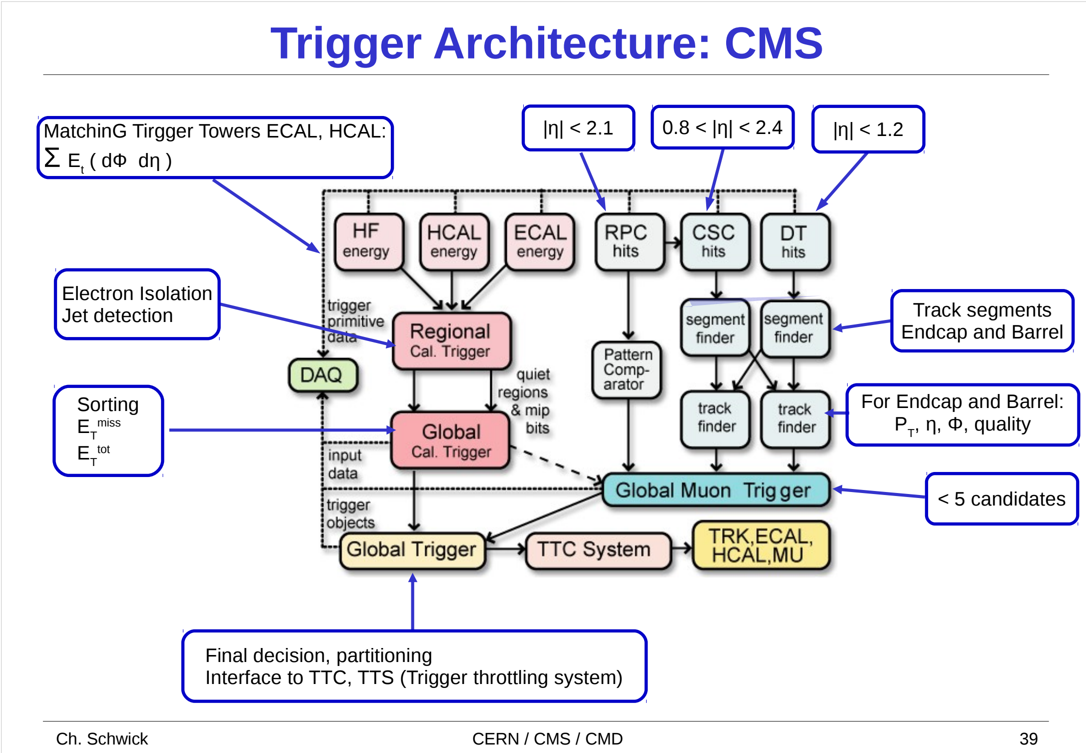
- **Jet trigger : work in large 3x3 region:**
  - $E_t^{central} > E_T^{threshold}$
  - $E_t^{central} > E_T^{neighbours}$

- **Tau trigger: work first in 4x4 regions**
  - Find localized small jets: If energy not confined in 2x2 tower pattern -> set Tau veto
  - Tau trigger: No Tau veto in all 9 clusters

One of the small boxes is 5x5 em towers

Step one: work in one CLUSTER
- energy confined in small reagion
  If found something outside the indicated red patterns patters: no tau

Step two: work on 3x3 CLUSTER
- isolation criteria



CONNECTION next slide: TTC

Calorimeter: Identify clusters and cut on shape and correlation ECAL,HCAL

3/gamma: Ehcal/Eecal < 5%

EtCenter + Et of max of one of 4 neighbours) > threshold etmin

Fine grain: 2 rows have minimal fraction of threshold etmin

isolated egamma: at least one corner is quiet (< etiso)

veto on HCAL energy works on all 8 neighbours

jets and taus: based on 3x3 (4x4 towers)blocks

center block must be higher thant 8 neigbours and greater than min threshold (5GeV)

tau veto: jet non confined in 2x2 tower region

Criterea on cluster shape in ECAL -> identify “isolated” e

Criterea on cluster shape in HCAL -> discriminate Jet agains Tau

Correlate clusters in ECAL and HCAL -> dsicriminate Jet,Tau against e/gamma

CMS : produce bits to find “isolated muons” : quiet regions (ECAL) and bits which show mip compatibility (HCAL)

Global Trigger

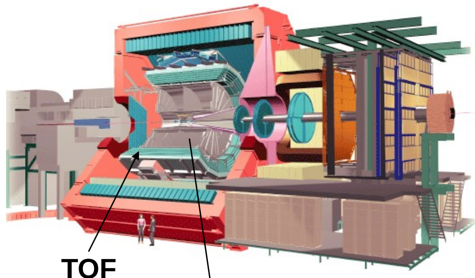
- **Forms final decision**
  - Programmable “Trigger Menu”
  - Logical “OR” of various trigger conditions
    - In Jargon these trigger conditions are called “triggers” themselves.
      The individual triggers may be downscaled (only take every 5th)
      Example:

1 μ	with Et > 20 GeV	**or**	“single muon trigger”
2 μ	with Et > 6 GeV	**or**	“di - muon trigger”
1 e/γ	with Et > 25 GeV	**or**	“single electron trigger”
2 e/γ	with Et > 15 GeV	**or**	“di - electron trigger”
	⋮		

Specific solutions for specific needs: ALICE and LHCb

ALICE: 3 hardware trigger levels

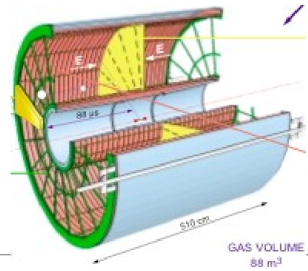
- **Some sub-detectors e.g. TOF (Time Of Flight) need very early strobe (1.2 μs after interaction)**
  - Not all subdetectors can deliver trigger signals so fast
  - Split 1st level trigger into :
  - **L0 : latency 1.2 μs**
  - **L1 : latency 6.5 μs**



TOF

- **ALICE uses a TPC for tracking**
  - TPC drift time: **88μs**
  - In Pb-Pb collisions only one interaction at a time can be tolerated
    (otherwise: too many tracks in TPC)
  - Need **pile-up protection**:
    - Makes sure there is only one event at time in TPC (need to wait for TPC drift time)
  - **L2 : latency 88μs**

TPC



L0: PHOS, EMCAL, DM TRD-pretrigegger
L1: TRD, ZDC, topological triggers

ALICE has 3 hardware trigger levels
Past-future protection is l2

ALICE: optimizing efficiency

- **Specific property of ALICE:**
  - Some sub-detectors need a long time to be read out after LVL2 trigger (e.g. Si drift detector: 260µs)
  - But: Some interesting physics events need only a subset of detectors to be read out.
- **Concept of Trigger clusters:**
  - Trigger cluster: group of sub-detectors
    - one sub-detector can be member of several clusters
  - Every trigger is associated to one Trigger Clusters
  - Even if some sub-detectors are busy due to readout: triggers for not-busy clusters can be accepted.
- **Triggers with “rare” classification:**
  - In general at LHC: stop the trigger if readout buffer almost full
  - ALICE:
    - “rare” triggers fire rarely and contain potentially interesting events.
    - when buffers get “almost-full” accept only “rare” triggers

2 interesting concepts can be found in the trigger concepts of ALICE:
There are subdetectors with long readout time for example: Silicon drift (260us)

Lvl0 : cable broadcast needed to strobe TOF; Lvl1 1,2 TTC

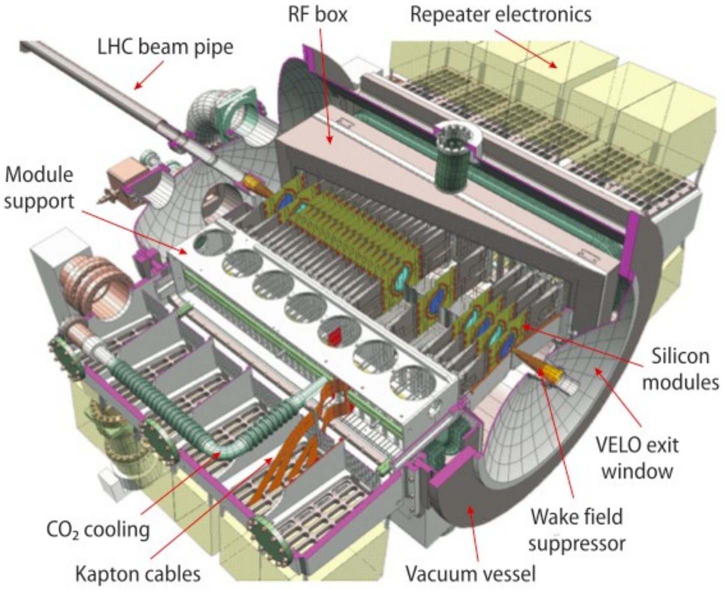
Similar to having more than one partition in physics run. Difference: a single detector can belong to more than one partition.

Sub detectors are grouped into “trigger clusters”
a single sub detector can belong to more than one trigger cluster

Every trigger is associated to a specific trigger cluster

During data taking some sub detectors take a long time to read out.
If during this time a trigger occurs which does not need to read out the busy detector it will be accepted and
2 events will be processed at the same time.

LHCb: VELO (Vertex Locator)

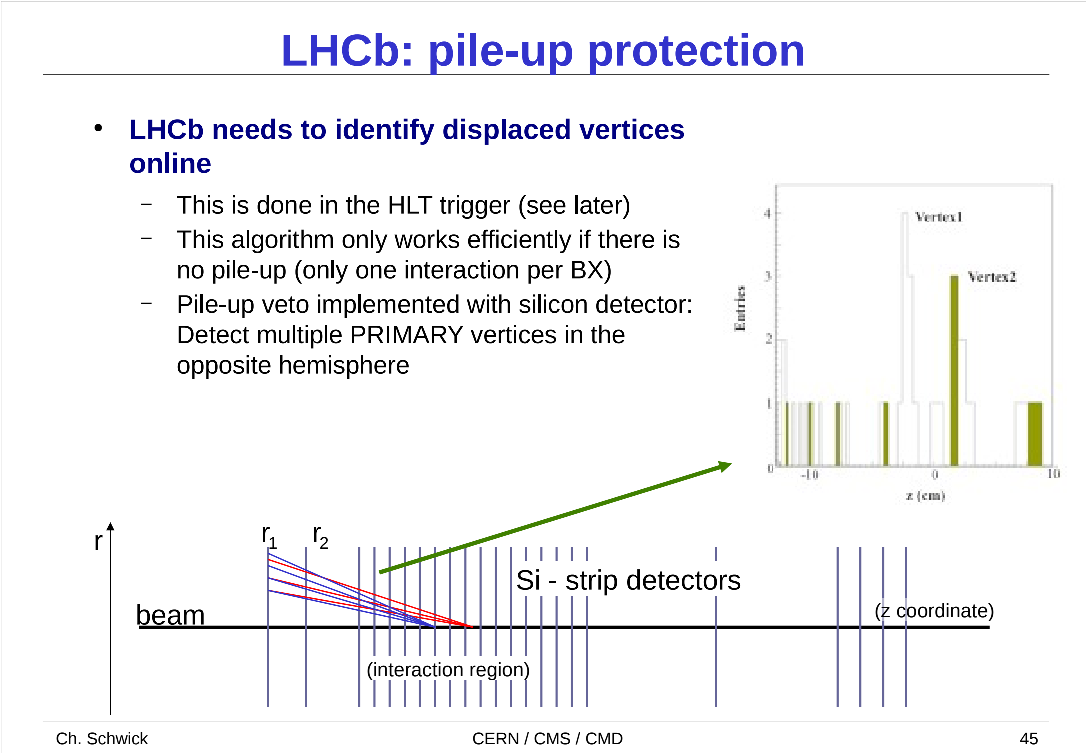


L0: High pt lepton,gamma or hadron 40MHz -> 1Mhz (10 MHz with >= 1 interaction at LHCb 2x10^32)
peak lumi 10^34
Pileup veto

HLT: look for 2 tracks with high impact parameter (secondary vertex)
inclusive and exclusive selections -> 2kHz to tape

Originally: Thought to be necessary since it would be too complicated in to disentangle more than one primary vertices. . In practice: showed to be possible to cope with up to 4 vertices (LHC started substantially later than originally foreseen).
Now this device is very useful to measure Lumi by counting primary vertices.

Upgrade: higher lumi would need to increase thresholds beyond B mass threshold -> no gain in physics
Take up to 100^-1 pb in 2015-2020



Veto on events with more than 1 or 2 vertices since they are difficult to process in hlt (pileup veto)
Search in oposite hemisphere in order not to veto events with interesting secondary vertices by B decays in the hemisphere under investigation

With a bit of arithmetics you can easily show that r1/r2 is a constant value for a given vertex on z-axis.

In practice: problem of vertices with very different multiplicities: to fight this
Make histogram of ration k=r1/r2
Find highest peak
Remove all hits which contribute to this peak
Do the histo again (now much better S/N since a lot of combinatorical background removed)
Look for secondary peaks.

Algo needs to treat 2048 nits at 40MHz = 80Gb/s and takes 80 BX: 2 us

LHCB works normally in p-p collisions-> veto looks in opposite hemisphere and therefore will not be triggered by displaced vertices of interesting b mesons in hemisphere under investigation

In order not to have too many multiple interactions in LHCB: the beams are slightly offset one from another -> lower luminosity

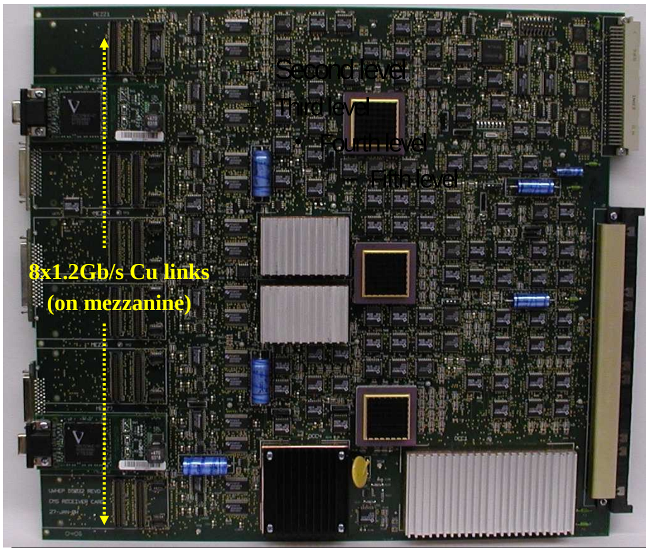
Truth: The silicon detector are half disks since they need do be retracted during beam injection (the beam would destroy the detector during injection since it is not yet perfectly focussed)

Trigger implementation

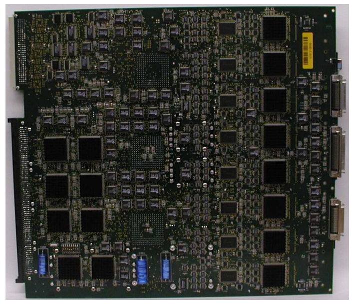
CMS: Regional Calorimeter Trigger

Receives 64 Trigger primitives from (32 ECAL, 32 HCAL)

Forms two 4x4 Towers for Jet Trigger and 16 ET towers for electron identification card

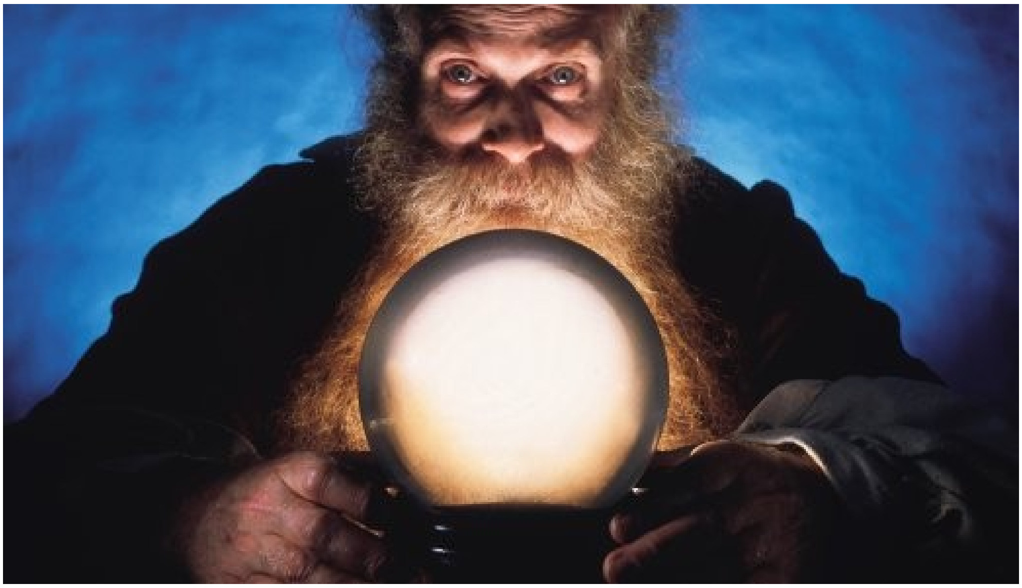


“solder” - side of the same card:



Sometimes physicists and engineers are driven to extreme solutions…

??? What does the future bring us ???



Trigger upgrades: Introduction

- **LHC plans to upgrade the accelerator in the next 2 years**
  - Energy will go from 8 TeV to 13 TeV
  - Peak Luminosity from $7x10^{33}$ to approx. $2x10^{34}$
  - Not yet clear if 25ns or 50ns bunch spacing
    - Remember the relation between this and Pileup
  - **Pileup might increase to values of 40-50**
    - The experiments were constructed for a pileup around 23

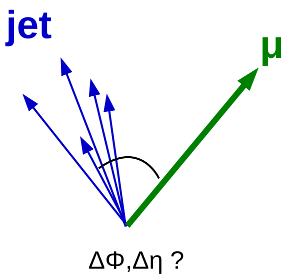
BX spacing [ns]	Beam current [$x10^{11}$ e]	Emittance [µm]	Peak Lumi [x $10^{34}cm^{-2}s^{-1}$]	Pileup
25	1.15	3.5	0.92	21
25	1.15	1.9	1.6	43
50	1.6	2.3	0.9-1.7	40-76
50	1.6	1.6	2.2	108

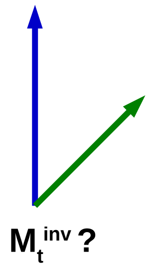
Trigger updates: Introduction

- **The high pileup degrades the performance of current trigger algorithms**
  - If nothing is done the rates exceed by far 100 kHz
- **The Higgs boson is relatively light (125 GeV)**
  - The future physics program foresees to investigate this boson with enhanced precision.
    - This means trigger **efficiencies need to stay** at least as good as they are.
    - **Trigger thresholds cannot be increased** without “cutting into the physics”
- **The experiments need to find ways to**
  cope with the higher pileup without loosing efficiency for physics
- **General solutions:**
  - Increase resolution for trigger object: Energy, Momentum, Spacial
    - Finer grain input data to trigger
      - More input data to the trigger
      - Enhance detectors in critical high multiplicity regions (forward region)
  - More complex algorithms
    - To be implemented in modern FPGAs
    - e.g. topological triggers, calculation of invariant mass, subtraction of pileup, ...
  - Include tracking in Lvl1 Trigger

Atlas Trigger Upgrade

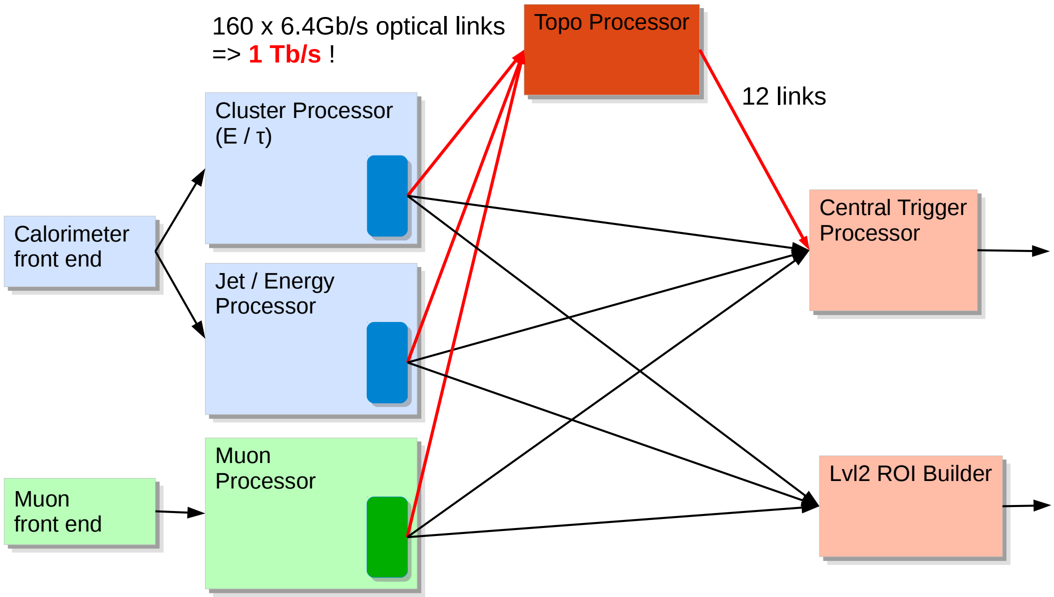
- **Keep trigger rates under control by using topology**
  - Use Trigger primitives of Lvl2: ROIs
  - Send them to dedicate topology processor based on powerful FPGAs
  - Calculate invariant masses, determine topologies like "back to back", measure rapidity gaps, ...





Need to process topological information at Lvl1

Topological Trigger: Concept



Atlas Topological Trigger

- **Nothing comes for free...: Latency**
  - Front-end pipelines are expensive resources: **Latency budget is tight**.
  - The Topology Processor is an **additional Processing Step** in Front of the Central Trigger Processor: It “eats” from the Latency Budget.

- **ATLAS has some latency contingency**
  - Around **12 BC** contingency in the L1 latency budget can be used for the topology processor
    - This limits the complexity and number of calculations which can be done

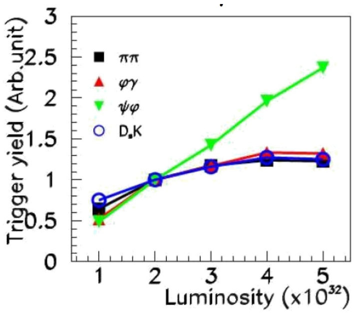
Does it make sense to upgrade LHCb ?

- **LHCb is a high statistics experiment**
  - LHCb is doing high precision measurements which are limited by statistics
  - To significantly improve the physics results of LHCb one should increase the statistics by a **factor of 10**

- **Where can LHCb gain a factor of 10 in statistics**
  - Currently LHCb takes data with $4x10^{32}$
    - Beams are on purpose separated a bit in LHCb to achieve reduce the Luminosity to this value
  - **Upgraded Lumi by factor of 5** to max. 20×10^{33}

Does it make sense to upgrade LHCb ?

- **Gain another factor of 2 in B → π π**
  - Currently efficiency of this channel is about 50% due to inefficiency in the first level trigger.
  - To gain back the 50% lost efficiency: plan to run without Hardware Trigger.



    - This means to construct a DAQ system with effectiv
    - Events at the luminosity of 10^{33} are expected to have 100kB
    - This results in a 30 Tb/s Event Builder!

  - As an emergency brake the Lvl0 Trigger will be kept and can be switched on.

Therefore...

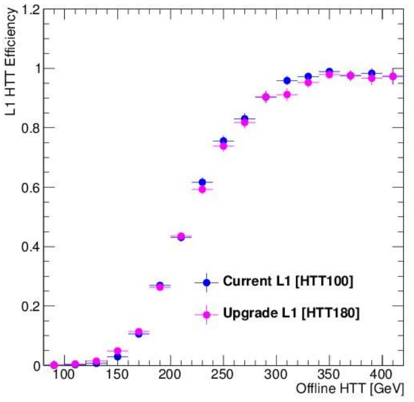
Yes, it DOES make sense to upgrade LHCb

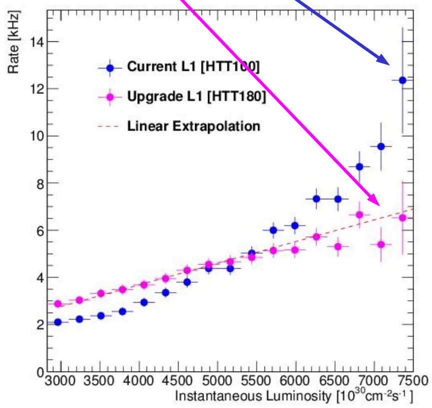
Calorimeter Trigger of CMS

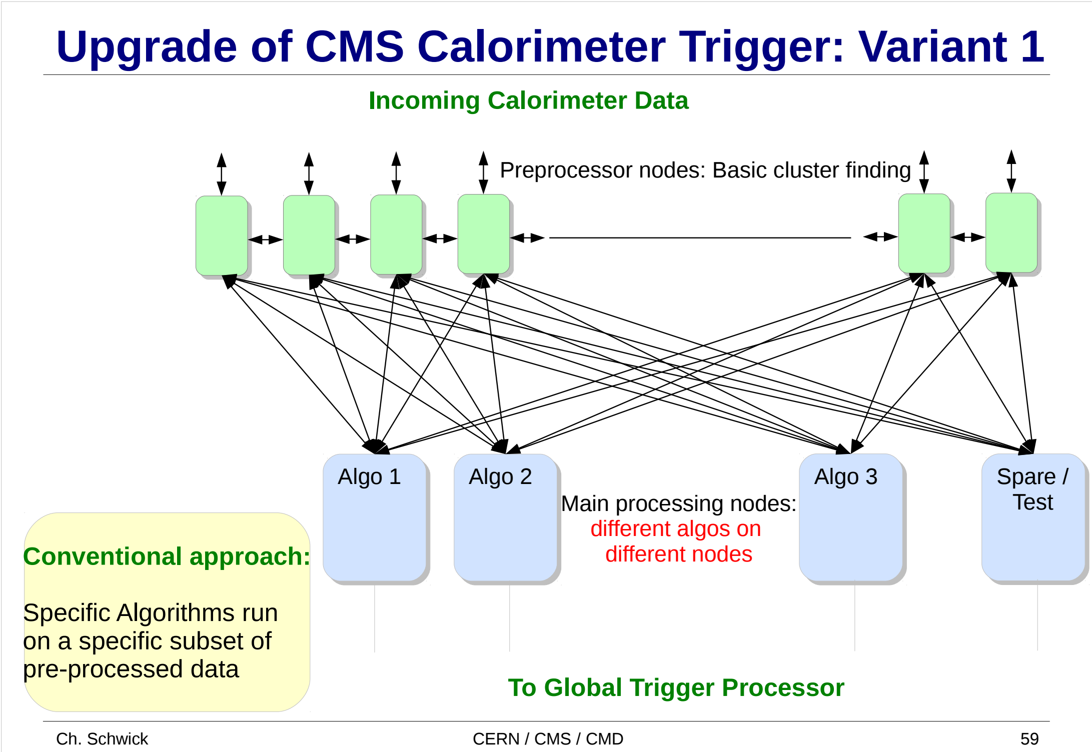
- **Upgrade of the Calorimeter Trigger electronics will bring improvements in various area**
  - Make use of full granularity of trigger primitives available.
    - (The current trigger is not able to exploit this)
  - The resulting better spacial resolution will allow to improve significantly the τ-trigger.
    - τ-triggers are based on finding small jets requiring good resolution

Calorimeter Trigger of CMS

- **More Complex Trigger Algos: Event by Event Pileup subtraction**
  - HTT : trigger on total transverse Jet Energy: At high pileup the rate of this trigger grows exponentially in the current system
  - With Pileup subtraction the trigger rate increases linearly with moderate slope





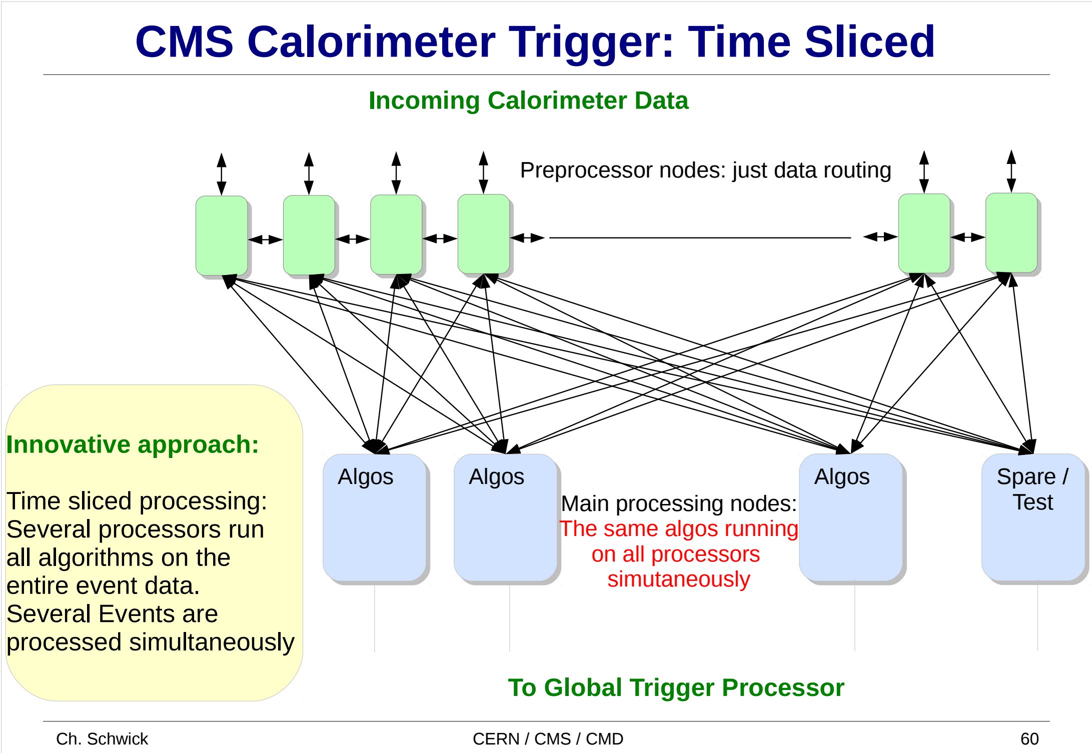


Pre-processing serves as data reduction

All algos run in parallel at the same time for the same event

The Algorithms do NOT have acess to the entire event data

Can try out new algoritms in parallel



Event 1 goes to first processor, event 2 to the second …

The second level processor contains all necessary algos

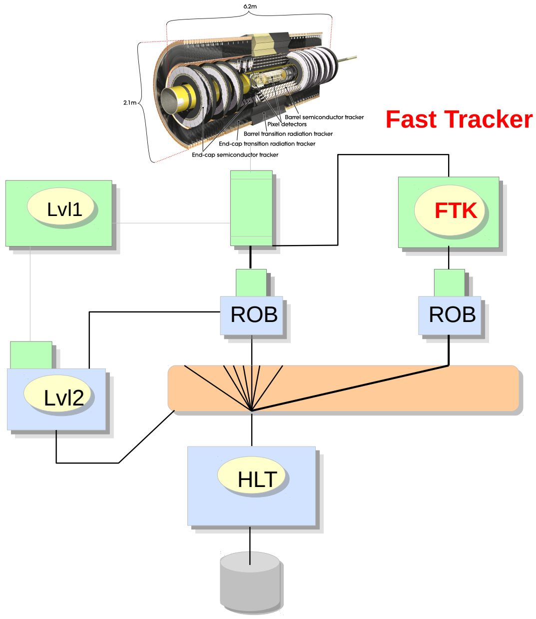
All information is available durign processing.
Algo results can be correlated

Processing starts as soon as data flows in.

Compare this to an Event Builder (see next talk): same way of functioning

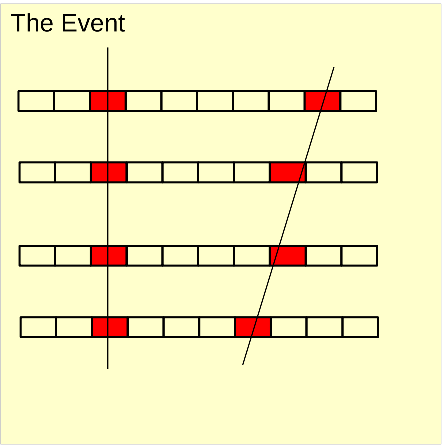
Atlas: First step to a Hw-Track Trigger

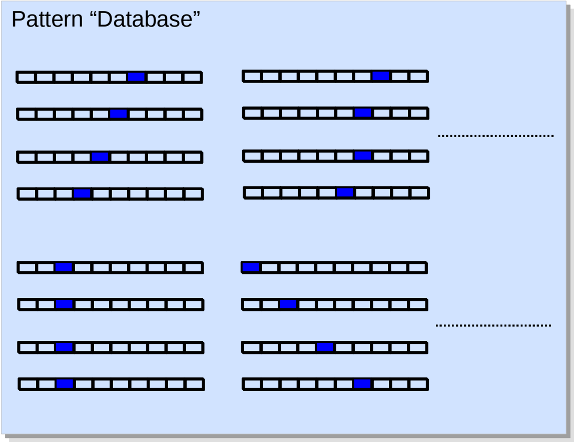
- **Track-finding is CPU intensive**
  - Especially in high pileup events the events the resources needed to do track-finding increase exponentially
- **Idea: Special highly parallel hardware processors should find tracks**
  - The output of the processor will be available at Lvl2 / Filter
  - The CPU time saved by not having to do tracking can be used for other trigger algorithms.



How to build a Hardware Tracker

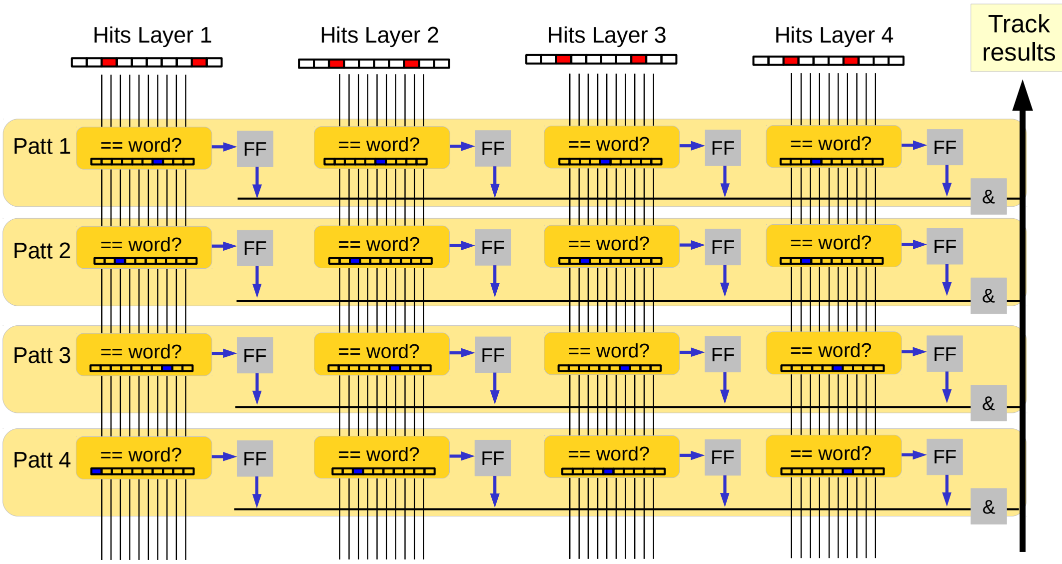
- **Compare the Event Hit Pattern with many Stored patterns**
  - The comparision with all patterns has to be done in parallel!





Implementation of Hardware Track Trigger

Principle of a CAM: Content Addressable Memory



Conclusion

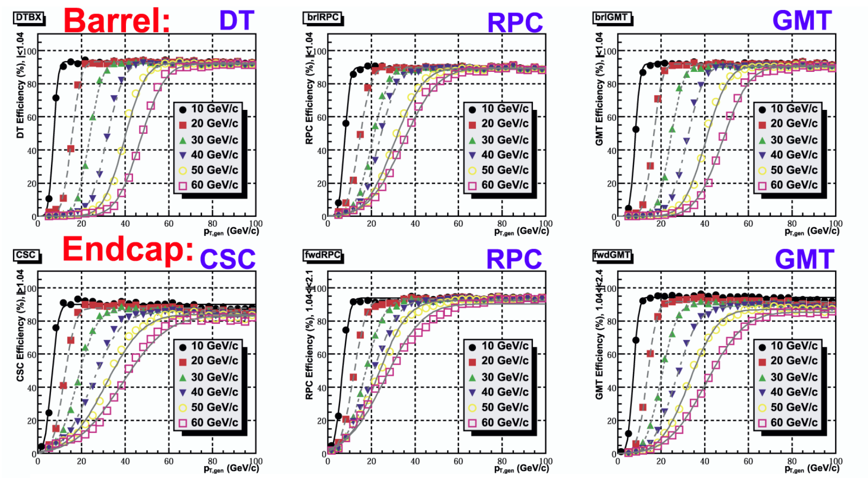
- **The concepts and techniques you learned in this school are widely applied in the LHC experiments.**

- **The design for the trigger of the LHC experiments is driven by**
  - Physics needs
  - Conditions of the accelerator
  - Compromises wrt budget

- **An exciting upgrade program has started in order to meet the experimental challenges after upgrade of the accelerator**

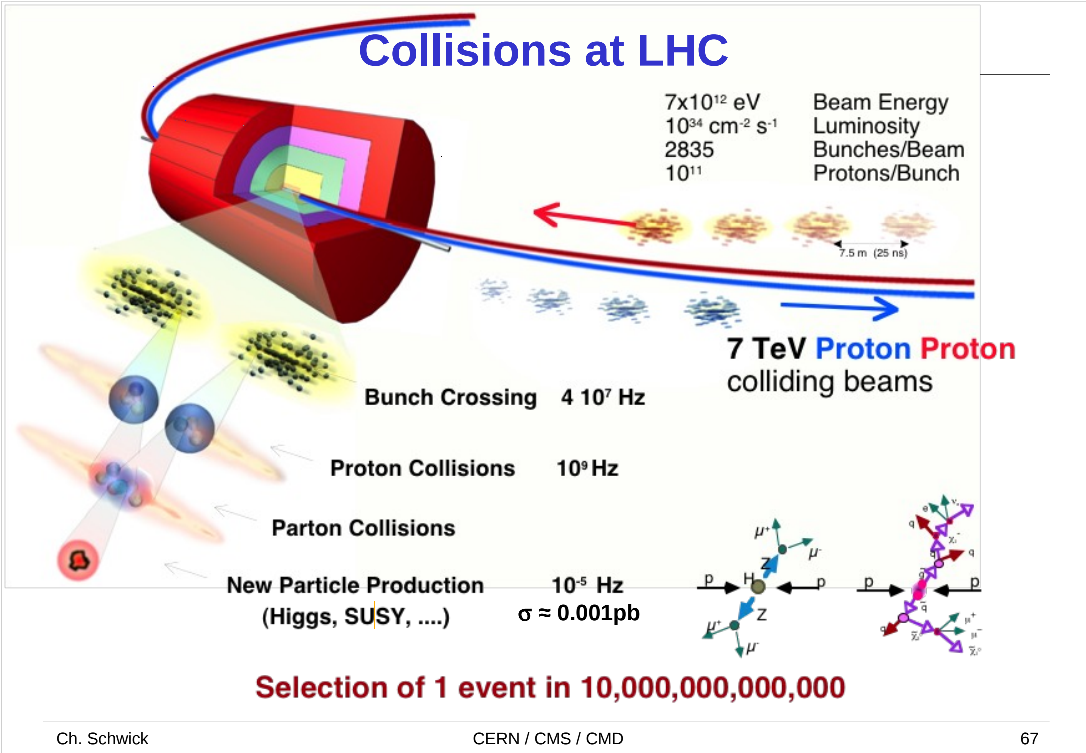
Extra slides: Lvl1 trigger

CMS Muon Trigger: Efficiency



MC with detector simulation
X-axis generated muon Pt   y-axe efficiency
No direct benefit visiable from having redundant systems (RPC +CSC/DT)

Not 100 % due to inefficient regions “holes in the detector”



Compare to e+ e- physics: small cross sections, no periphal collisions (almost)
Always when there is a signal in the detector you could afford to look at the data closely (later more)
Lvl1 Trigger rate order of 15-20 Hz!

Level-1 trigger "cocktail" (low/high lumi)

Low Luminosity

Total Rate: 50 kHz
Factor 3 safety,
allocate 16 kHz

Trigger	Threshold (e=90-95%) (GeV)	Indiv. Rate (kHz)	Cumul rate(kHz)
1e/g, 2e/g	29, 17	4.3	4.3
1m, 2m	14, 3	3.6	7.9
1t, 2t	86, 59	3.2	10.9
1-jet	177	1.0	11.4
3-jets, 4-jets	86, 70	2.0	12.5
Jet & Miss-ET	88 & 46	2.3	14.3
e & jet	21 & 45	0.8	15.1
Min-bias		0.9	16.0

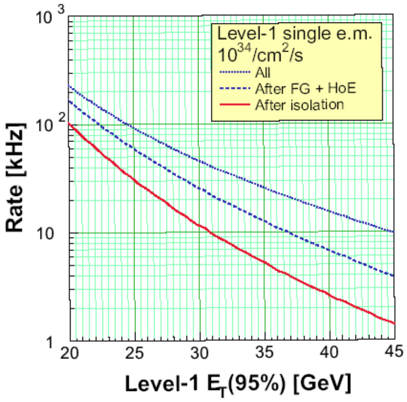
High Luminosity

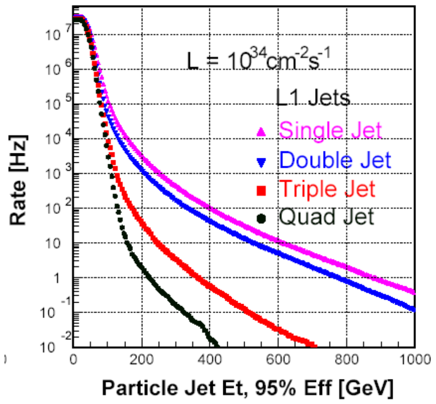
Total Rate: 100 kHz
Factor 3 safety,
allocate 33.5 kHz

Trigger	Threshold (e=90-95%) (GeV)	Indiv. Rate (kHz)	Cumul rate (kHz)
1e/g, 2e/ g	34, 19	9.4	9.4
1m, 2m	20, 5	7.9	17.3
1t, 2t	101, 67	8.9	25.0
1-jet	250	1.0	25.6
3-jets, 4-jets	110, 95	2.0	26.7
Jet & Miss-ET	113 & 70	4.5	30.4
e & jet	25 & 52	1.3	31.7
m & jet	15 & 40	0.8	32.5
Min-bias		1.0	33.5

Min bias: random trigger to study trigger performance!

Calorimeter trigger: rates

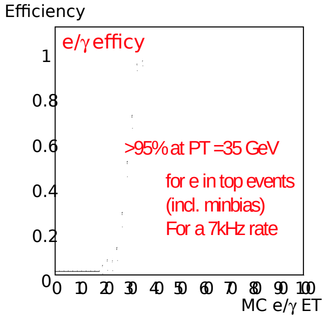


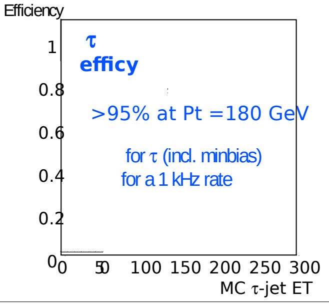


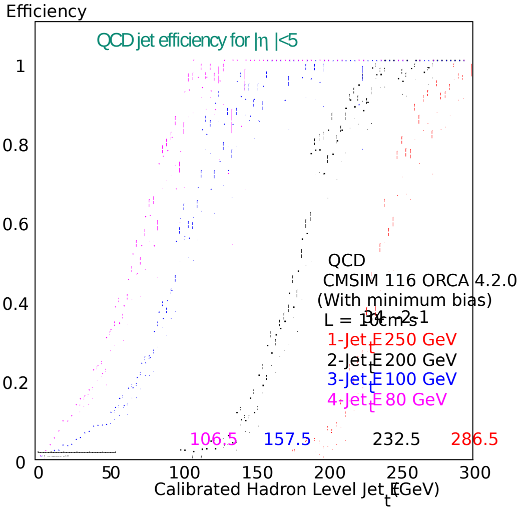
- Simulation

For your reference, do not discuss in detail

Calorimeter trigger: rates (Simulation)







>95% at PT =286, 232, 157, 106 GeV for individual 1,2,3,4 jet triggers (incl. minbias)

(~0.5 kHz rate each totaling ~2 kHz)

Potentially interesting event categories

- **Standard Model Higgs**
  - If Higgs is light (< 160GeV) : H -> $\gamma\gamma$ H -> ZZ* -> 4l
  - Trigger on electromagnetic clusters, lepton-pairs
  - If Higgs is heavier other channels will be used to detect it
  - H -> ZZ -> ll$\nu\nu$
  - H -> WW -> lνjj
  - H -> ZZ -> lljj
  - Need to trigger on lepton pairs, jets and missing energies

- **Supersymmetry**
  - Neutralinos and Gravitinos generate events with missing Etmiss
  - Squarks decay into multiple jets
  - Higgs might decay into 2 taus (which decay into narrow jets)

Trigger at LHC startup: L=1033cm-2s-1

- **LHC startup**
  - Factor 10 less pile up O(2) interactions per bunch crossing
  - Much less particles in detector
  - Possible to run with lower trigger thresholds

- **B-physics**
  - Trigger on leptons
  - In particular: muons (trigger thresholds can be lower than for electrons)

- **t-quark physics**
  - Trigger on pairs of leptons.

LHCb

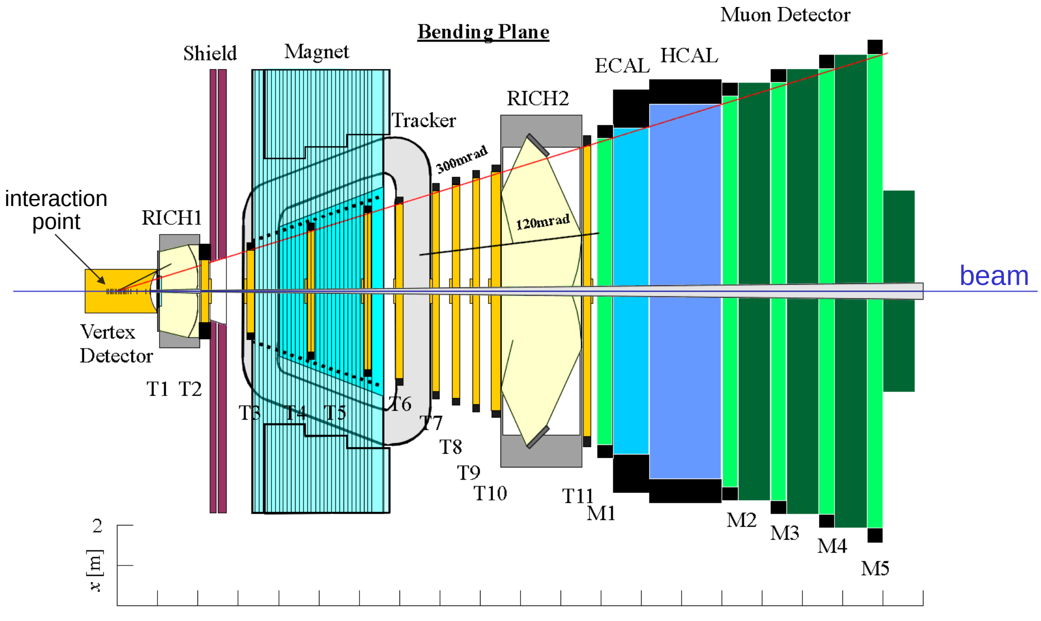
- **Operate at L = 2 x 1032 cm-2s-1: 10 MHz event rate**

- **Lvl0: 2-4 us latency, 1MHz output**
  - Pile-up veto, calorimeter, muon

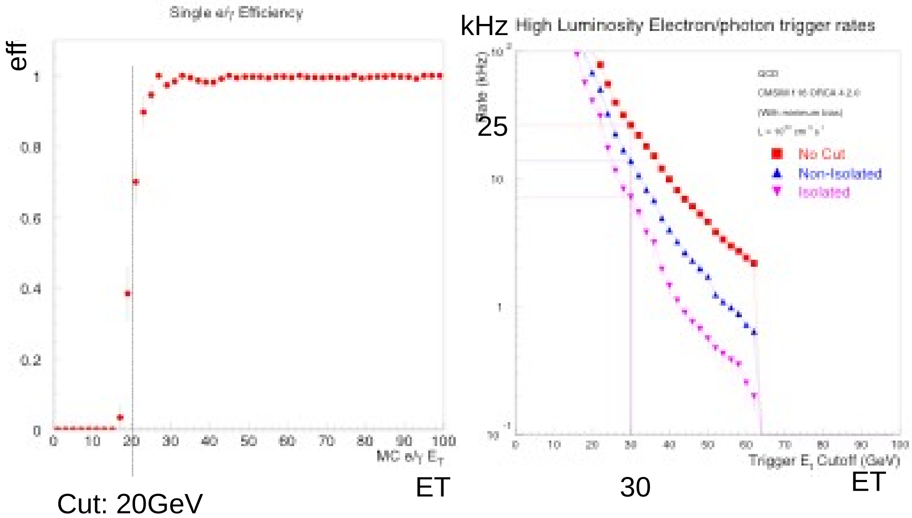
- **Pile up veto**
  - Can only tolerate one interaction per bunch crossing since otherwise always a displaced vertex would be found by trigger

Lvl1 measures also Pt in calorimeter and muons

LHCb : study of B-decays (CP)



CMS isolated e/γ performance



Red: input of MC (no cuts at all)
Blue : Electron cuts 12kHz
Purple demand isolation 7kHz

The 1st level trigger at LHC experiments

Requirement:

Do not introduce (a lot of) dead-time

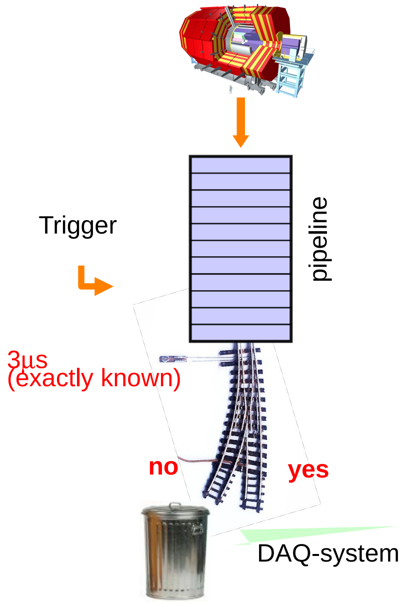
- O(1%) is tolerated
- Introduced by trigger rules :
  not more than n triggers in m BX
- Needed by FE electronics

Need to implement pipelines

- Need to store data of all BX for latency of 1st level trigger
- Typical : 107 channels / detector
  some GB pipeline memory
  - and derandomizer buffers
- Also the trigger itself is “pipelined”

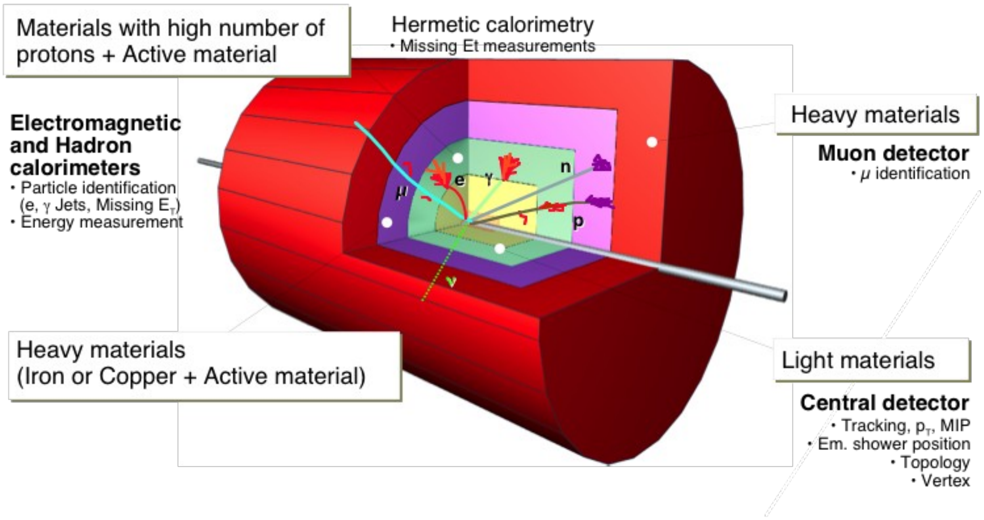
Trigger must have low latency (2-3 µs)

- Otherwise pipelines would have to be very long



NOT possible to make a decision in 25 ns (need 2-3uss)
NOT possible to analyse all in 2-3 us
Dead time: Detector becomes “insensitive” for new events during a period
Pipeline: like a shift register
Important: latency exactly known

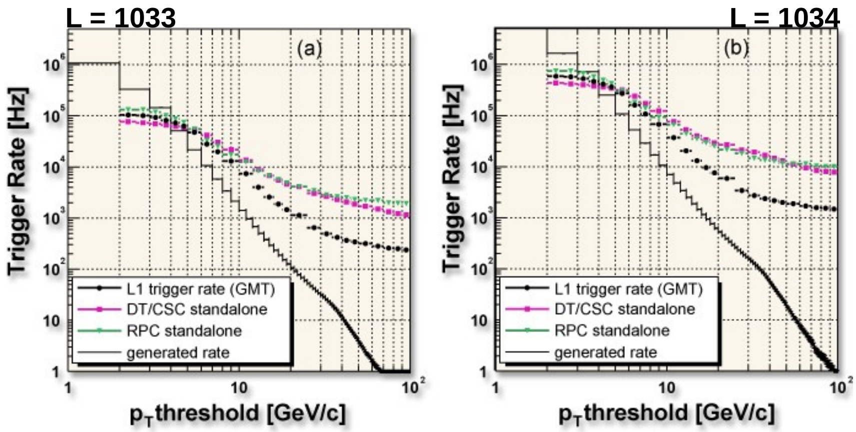
LHC Detector: main principle



Each layer identifies and enables the measurement of the momentum or energy of the particles produced in a collision

Redundancy in the CMS Muon trigger

Generated Muons versus trigger rate (simulation)



pt > 20GeV:
≈ 100 Hz generated,
≈ 1 kHz trigger rate

pt > 20GeV:
≈ 600 Hz generated,
≈ 8 kHz trigger rate

This plot is done WITH detector simulation! The previous not!

You see how redundancy in the trigger system helps

Show why multiple detectors are useful here: redundancy allows to reduce the trigger rate (cutting on quality no of hits, …)

Triggering at LHC : what info can be used

- **Measurements with Calorimeters and Muon chamber system**

- **Transverse Momentum of muons**
  - Measurement of muon p_t in magnetic field
  - p_t is the interesting quantity:
    - Total p_t is 0 before parton collision (pt conservation)
    - High p_t is indication of hard scattering process (i.e. decay of heavy particle)
    - Detectors can measure precisely p_t
    -

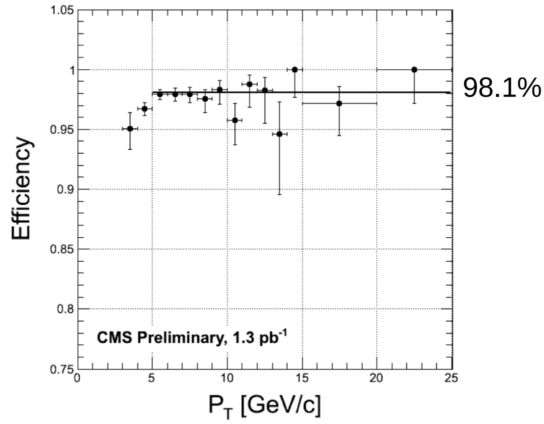
- **Energy**
  - Electromagnetic energy for electrons and photons
  - Hadronic energy for jet measurements, jet counting, tau identification
  - Like for momentum measurement: E_t is the interesting quantity
  - Missing E_t can be determined (important for new physics)

Pz is not 0 at parton collision but depends on momenum distribution of quarks in

Side remark: pT is the transverse momentum (px, py) in plane perpendicular to beam. pT is a key quantitiy to characterize an event since detectors can measure precisely pT (but much less precisely pz. Reasons: orientation of magnetic field, particle density in endcap region. Interesting events are expected to be in the low rapidity region anyway-> detectors have been optiimized for this)

Muon Track Finding Efficiency (CMS DT)

- **Technique tag & probe**
  - J/Ψ -> μμ,
  - one μ satisfied trigger, the other used to measure efficiency
  - Inefficiency understood hardware problem



With the probe muon you should always find a track
Here we do not care with which Pt but only that a track is found
(x axis is pt of tag muon)
We see that it is not 100% due to some hardware issues

Trigger implementation (II)

- **ASIC (Application Specific Integrated Circuit)**
  - Can be produced radiation tolerant (for “on detector” electronics)
  - Can contain “mixed” design: analog and digital electronics
  - Various design methods: from transistor level to high level libraries
  - In some cases more economic (large numbers, or specific functionality)
  - Disadvantages:
  - Higher development “risk” (a development cycle is expensive)
  - Long development cycles than FPGAs
    - No bugs tolerable -> extensive simulation necessary

- **Example :**
  - ASIC to determine ET and to identify the Bunch Crossing (BX) from the ATLAS calorimeter signals
  - Coincidence matrix in Muon Trigger of ATLAS

Trigger implementation (III)

- **Key characteristics of Trigger Electronic boards**
  - Large cards because of large number of IO channels
  - Many identical channels processing data in parallel
  - This keeps latency low
  - Pipelined architecture
  - New data arrives every 25ns
  - Custom high speed links
  - Backplane parallel busses for in-crate connections
  - LVDS links for short (O(10m)) inter-crate connections
    (LVDS: Low Voltage Differential Signaling)